SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the process was the development of a foundational technical input report (TIR), "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] A public session conducted as part of the Tri-Societies (https://www.acsmeetings.org/home) meeting held in San Antonio, Texas, on Oct. 16-19, 2011, provided input to this report.

The report team engaged in multiple technical discussions via teleconference, which included careful review of the foundational TIR[15] and of approximately 56 additional technical inputs provided by the public, as well as other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors and targeted consultation with additional experts by the lead author of each message.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Climate disruptions to agricultural production have increased in the past 40 years and are projected to increase over the next 25 years. By mid-century and beyond, these impacts will be increasingly negative on most crops and livestock.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation.[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that climate change has had and will have impacts on crops and livestock is based on numerous studies and is incontrovertible.[6,7,8]

The literature strongly suggests that carbon dioxide, temperature, and precipitation affect livestock and crop production. Plants have an optimal temperature range to which they are adapted, and regional crop growth will be affected by shifts in that region's temperatures relative to each crop's optimal range. Large shifts in temperature can significantly affect seasonal biomass growth, while changes in the timing and intensity of extreme temperature effects are expected to negatively affect crop development during critical windows such as pollination. Crop production will also be affected by changing patterns of seasonal precipitation; extreme precipitation events are expected to occur more frequently and negatively affect production levels. Livestock production is directly affected by extreme temperature as the animal makes metabolic adjustments to cope with heat stress.[15] Further, production costs in confined systems markedly increase when climate regulation is necessary.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture,[82] which informed the 2009 National Climate Assessment.[83]

There is insufficient understanding of the effects on crop production of rising carbon dioxide, changing temperatures and more variable precipitation patterns.[9] The combined effects on plant water demand and soil water availability will be critical to understanding regional crop response. The role of increasing minimum temperatures on water demand and growth and senescence rates of plants is an important factor. There is insufficient understanding of how prolonged exposure of livestock to high or cold temperatures affects metabolism and reproductive variables.[26] For grazing animals, climate conditions during the growing season are critical in determining feed availability and quality on rangeland and pastureland.[69]

The information base can be enhanced by evaluating crop growth and livestock production models. This evaluation would further the understanding of the interactions of climate variables and the biological system. Better understanding of projected changes in precipitation will narrow uncertainty about future yield reductions.[9,69]

Assessment of confidence based on evidence

There are a range of controlled environment and field studies that provide the evidence for these findings. Confidence in this key message is therefore judged to be **high**.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Many agricultural regions will experience declines in crop and livestock production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe the direct effects of climate on the ecological systems within which crop and livestock operations occur. Many weeds respond more strongly to CO_2 than do crops, and it is believed that the range of many diseases and pests (for both crop and livestock) will expand under warming conditions.[28,31,40] Pests may have increased overwinter survival and fit more generations into a single year, which may also facilitate faster evolution of pesticide resistance. Changing patterns of pressure from weeds, other pests, and disease can affect crop and livestock production in ways that may be costly or challenging to address.[9,15]

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture,[82] which informed the 2009 National Climate Assessment.[83]

In addition to extant species already in the U.S., exotic weeds, diseases, and pests have particular significance in that: 1) they can often be invasive (that is, arrive without normal biological/ecological controls) and highly damaging; 2) with increasing international trade, there are numerous high-threat, high-impact species that will arrive on commodities from areas where some species even now are barely known to modern science, but which have the potential to emerge under a changed climate regime to pose significant risk of establishment in the U.S. and economic loss; and 3) can take advantage of "disturbances," where climate variability acts as an additional ecological disturbance. Improved models and observational data related to how many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses will need to be developed.

A key issue is the extent of the interaction between components of the natural biological system (for example, pests) and the economic biological system (for example, crop or animal). For insects, increased populations are a factor; however, their effect on the plant may be dependent upon the phenological stage of the plant when the insect is at specific phenological stages.[15]

To enhance our understanding of these issues will require a concerted effort to begin to quantify the interactions of pests and the economic crop or livestock system and how each system and their interactions are affected by climate.[15]

Assessment of confidence based on evidence

The scientific literature is beginning to emerge; however, there are still some unknowns about the effects of biotic stresses, and there may well be emergent "surprises" resulting from departures from past ecological equilibria. Confidence is therefore judged to be **medium** that many agricultural regions will experience declines in animal and plant production from increased stress due to weeds, diseases, insect pests, and other climate change induced stresses.

Key message #3 Traceable Account

Current loss and degradation of critical agricultural soil and water assets due to increasing extremes in precipitation will continue to challenge both rainfed and irrigated agriculture unless innovative conservation methods are implemented.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation."[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Soil erosion is affected by rainfall intensity and there is evidence of increasing intensity in rainfall events even where the annual mean is reduced.[53] Unprotected soil surfaces will have increased erosion and require more intense conservation practices.[58,59] Shifts in seasonality and type of precipitation will affect both timing and impact of water availability for both rainfed and irrigated agriculture. Evidence is strong that in the future there will be more precipitation globally, and that rain events will be more intense, even if separated by longer periods without rain.[6]

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture,[82] which informed the 2009 National Climate Assessment.[83] Both rainfed and irrigated agriculture will increasingly be challenged, based on improved models and observational data related to the effects of increasing precipitation extremes on loss and degradation of critical agricultural soil and water assets.[51,52]

Precipitation shifts are the most difficult to project, and uncertainty in regional projections increases with time into the future.[61] To improve these projections will require enhanced understanding of shifts in timing, intensity, and magnitude of precipitation events. In the northern U.S., more frequent and severe winter and spring storms are projected, while there is a projected reduction in precipitation in the Southwest (see Ch. 2: Our Changing Climate).

Assessment of confidence based on evidence

The precipitation forecasts are the limiting factor in these assessments; the evidence of the impact of precipitation extremes on soil water availability and soil erosion is well established. Confidence in this key message is therefore judged to be **high**.

KEY MESSAGE #4 TRACEABLE ACCOUNT

The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Agriculture TIR, "Climate Change and Agriculture in the United States: An Assessment of Effects and Potential for Adaptation".[15] Additional Technical Input Reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications[6,61,62] provide evidence that the occurrence of extreme events is increasing, and exposure of plants or animals to temperatures and soil water conditions (drought, water-logging, flood) outside of the biological range for the given species will cause stress and reduce production.[6,61,62] The direct effects of an extreme event will depend upon the timing of the event relative to the growth stage of the biological system.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings in the past Synthesis and Assessment Product on agriculture, [82] which informed the 2009 National Climate Assessment.[83]

One key area of uncertainty is the timing of extreme events during the phenological stage of the plant or the growth stage of the animal. For example, plants are more sensitive to extreme high temperatures during the pollination stage compared to vegetative growth stages.[9] A parallel example for animals is relatively strong sensitivity to high temperatures during the conception phase.[34] Milk and egg production are also vulnerable to temperature extremes. The effects of extreme combinations of weather variables must be considered, such as elevated humidity in concert with high temperatures.[34]

Other key uncertainties include inadequate precision in simulations of the timing of extreme events relative to short time periods of crop vulnerability, and temperatures close to key thresholds such as freezing.[22] The uncertainty is amplified by the rarity of extreme events; this rarity means there are infrequent opportunities to study the impact of extreme events. In general, a shift of the distribution of temperatures can increase the frequency of threshold exceedance.[15]

The information base can be enhanced by improving the forecast of extreme events, given that the effect of extreme events on plants or animals is known.[3,61]

Assessment of confidence based on evidence

There is **high** confidence in the effects of extreme temperature events on crops and livestock, and the agreement in the literature is good.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Agriculture has been able to adapt to recent changes in climate; however, increased innovation will be needed to ensure the rate of adaptation of agriculture and the associated socioeconomic system can keep pace with climate change over the next 25 years.

Description of evidence base

There is emerging evidence about the economic impacts of climate change on agriculture and the potential for adaptive strategies.[64] In the case of crop production, much of the economic literature suggests that in the short term, producers will continue to adapt to weather changes and shocks as they always have, with changes in the timing of field operations, shifts in crops grown, and changing tillage or irrigation practices.[64] In the longer term, however, existing adaptive technologies will likely not be sufficient to buffer the impacts of climate change without significant impacts to domestic producers, consumers, or both.

New strategies for building long-term resilience include both new technologies and new institutions to facilitate appropriate, informed producer response to a changing climate. Furthermore, there are both public and private costs to adjusting agricultural production and infrastructure in a manner that enables adaptation.[2]

New information and remaining uncertainties

Limits to public investment and constraints on private investment could slow the speed of adaptation, yet potential constraints and limits are not well-understood or integrated into economic impact assessments. The economic implications of changing biotic pressures on crops and livestock, and on the agricultural system as a whole, are not well-understood, either in the short or long term.[15] Adaptation may also be limited by availability of inputs (such as land or water), changing prices of other inputs with climate change (such as energy and fertilizer), and by the environmental implications of intensifying or expanding agricultural production.

It is difficult to fully represent the complex interactions of the entire socio-ecological system within which agriculture operates, to assess the relative effectiveness and feasibility of adaptation strategies at various levels. Economic impact assessments require improved understanding of adaptation capacity and agricultural resilience at the system level, including the agri-ecosystem impacts related to diseases and pests. Economic impact assessments also require improved understanding of adaptation opportunities, economic resilience, and constraints to adaptation at the producer level.[2,64] The economic value of ecological services, such as pollination services, is particularly difficult to quantify and incorporate into economic impact efforts.[15]

Assessment of confidence based on evidence

Emerging evidence about adaptation of agricultural systems to changing climate is beginning to be developed. The complex interactions among all of the system components present a limitation to a complete understanding, but do provide a comprehensive framework for the assessment of agricultural responses to climate change. Given the overall and remaining uncertainty, there is **medium** confidence in this message.

KEY MESSAGE #6 TRACEABLE ACCOUNT

Climate change effects on agriculture will have consequences for food security, both in the U.S. and globally, through changes in crop yields and food prices and effects on food processing, storage, transportation, and retailing. Adaptation measures can help delay and reduce some of these impacts.

Description of evidence base

The relationships among agricultural productivity, climate change, and food security have been documented through ongoing investigations by the Food and Agriculture Organization,[81,84] as well as the U.S. Department of Agriculture,[85] and the National Research Council.[77] There are many factors that affect food security, and agricultural yields are only one of them. Climate change is also expected to affect distribution of food- and waterborne diseases, and food trade and distribution.[78]

New information and remaining uncertainties

The components of food security derive from the intersection of political, physical, economic, and social factors. In many ways the impact of climate change on crop yields is the least complex of the factors that affect the four components of food security (availability, stability, access, and utilization). As the globalized food system is subject to conflicting pressures across scales, one approach to reducing risk is a "cross-scale problem-driven" approach to food security.[76] This and other approaches to understanding and responding to the complexities of the global food system need additional research. Climate change will have a direct impact on crop and livestock production by increasing the variability in production levels from year to year, with varying effects across different regions. Climate change will also affect the distribution of food supplies as a result of disruptions in transportation routes. Addressing food security will require integration of multiple factors, including the direct and indirect impacts of climate change.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainty, there is **high** confidence that climate change impacts will have consequences for food security both in the U.S. and globally through changes in crop yields and food prices, and **very high** confidence that other related factors, including food processing, storage, transportation, and retailing will also be affected by climate change. There is **high** confidence that adaptation measures will help delay and reduce some of these impacts.

Climate Change Impacts in the United States

CHAPTER 7
FORESTS

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On the Web: http://nca2014.globalchange.gov/report/sectors/forests

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

7 FORESTS

Key Messages

1. **Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks.**
2. **U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest CO_2 uptake.**
3. **Bioenergy could emerge as a new market for wood and could aid in the restoration of forests killed by drought, insects, and fire.**
4. **Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy.**

Forests occur within urban areas, at the interface between urban and rural areas (wildland-urban interface), and in rural areas. Urban forests contribute to clean air, cooling buildings, aesthetics, and recreation in parks. Development in the wildland-urban interface is increasing because of the appeal of owning homes near or in the woods. In rural areas, market factors drive land uses among commercial forestry and land uses such as agriculture. Across this spectrum, forests provide recreational opportunities, cultural resources, and social values such as aesthetics.[1]

Economic factors have historically influenced both the overall area and use of private forestland. Private entities (such as corporations, family forest owners, and tribes) own 56% of the forestlands in the United States. The remaining 44% of forests are on public lands: federal (33%), state (9%), and county and municipal government (2%).[2] Market factors can influence management objectives for public lands, but societal values also influence objectives by identifying benefits such as environmental services not ordinarily provided through markets, like watershed protection and wildlife habitat. Different challenges and opportunities exist for public and for private forest management decisions, especially when climate-related issues are considered on a national scale. For example, public forests typically carry higher levels of forest biomass, are more remote, and tend not to be as intensively managed as private forestlands.[1]

Forests provide opportunities to reduce future climate change by capturing and storing carbon, as well as by providing resources for bioenergy production (the use of forest-derived plant-based materials for energy production). The total amount of carbon stored in U.S. forest ecosystems and wood products (such as lumber and pulpwood) equals roughly 25 years of U.S. heat-trapping gas emissions at current rates of emission, providing an important national "sink" that could grow or shrink depending on the extent of climate change, forest management practices, policy decisions, and other factors.[3,4] For example, in 2011, U.S. forest ecosystems and the associated wood products industry captured and stored roughly 16% of all carbon dioxide emitted by fossil fuel burning in the United States.[3]

Management choices for public, private, and tribal forests all involve similar issues. For example, increases in wildfire, disease, drought, and extreme events are projected for some regions (see also Ch. 16: Northeast; Ch. 20: Southwest; Ch. 21: Northwest, Key Message 3; and Ch. 22: Alaska). At the same time, there is growing awareness that forests may play an expanded role in carbon management. Urban expansion fragments forests and may limit forest management options. Addressing climate change effects on forestlands requires considering the interactions among land-use practices, energy options, and climate change.[5]

Key Message 1: Increasing Forest Disturbances

Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks.

Insect and pathogen outbreaks, invasive species, wildfires, and extreme events such as droughts, high winds, ice storms, hurricanes, and landslides induced by storms[8] are all disturbances that affect U.S. forests and their management (Figure 7.1). These disturbances are part of forest dynamics, are often interrelated, and can be amplified by underlying trends – for example, decades of rising average temperatures can increase damage to forests when a drought occurs.[9] Disturbances that affect large portions of forest ecosystems occur relatively infrequently and in response to climate extremes. Changes in climate in the absence of extreme climate events (and the forest disturbances they trigger) may result in increased forest productivity, but extreme climate events can potentially overturn such patterns.[10]

Factors affecting tree death – such as drought, physiological water stress, higher temperatures, and/or pests and pathogens – are often interrelated, which means that isolating a single cause of mortality is rare.[11,12,13] However, in western forests there have been recent large-scale die-off events due to one or more of these factors,[14,15,16] and rates of tree mortality are well correlated with both rising temperatures and associated increases in evaporative water demand.[17] In eastern forests, tree mortality at large spatial scales was more sensitive

Forest Ecosystem Disturbances

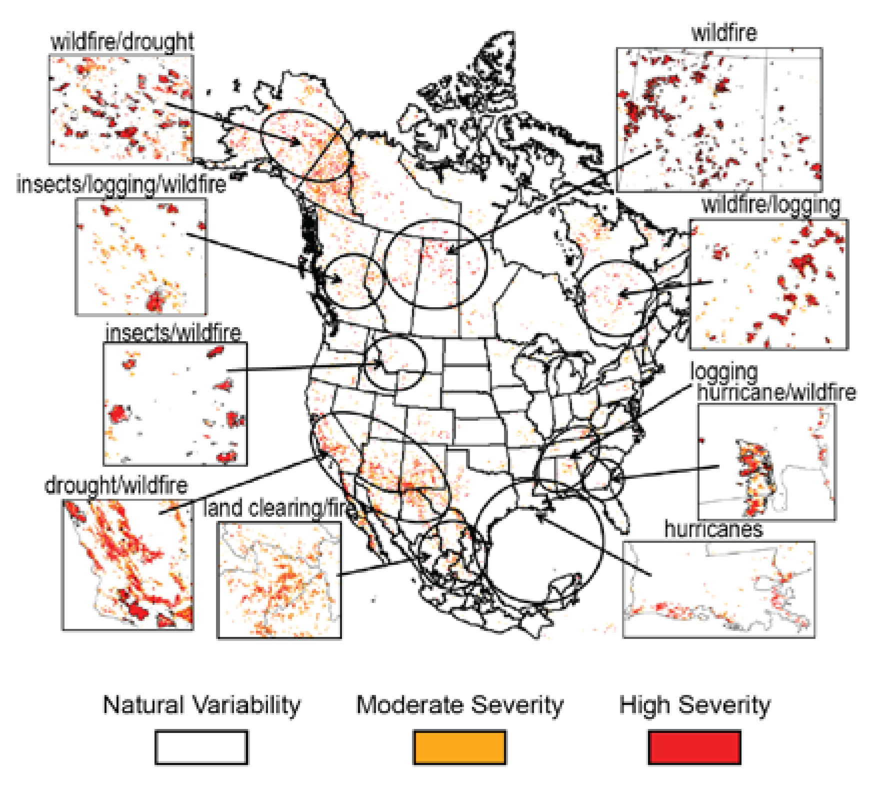

Figure 7.1. An example of the variability and distribution of major ecosystem disturbance types in North America, compiled from 2005 to 2009. Forest disturbance varies by topography, vegetation, weather patterns, climate gradients, and proximity to human settlement. Severity is mapped as a percent change in a satellite-derived Disturbance Index. White areas represent natural annual variability, orange represents moderate severity, and red represents high severity.[6] Fire dominates much of the western forest ecosystems, and storms affect the Gulf Coast. Insect damage is widespread but currently concentrated in western regions, and timber harvest is predominant in the Southeast. (Figure source: modified from Goetz et al. 2012;[7] Copyright 2012 American Geophysical Union).


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A Montana saw mill owner inspects a lodgepole pine covered in pitch tubes that show the tree trying, unsuccessfully, to defend itself against the bark beetle. The bark beetle is killing lodgepole pines throughout the western U.S.


© Pete McBride/National Geographic Creative

Warmer winters allow more insects to survive the cold season, and a longer summer allows some insects to complete two life cycles in a year instead of one. Drought stress reduces trees' ability to defend against boring insects. Above, beetle-killed trees in Rocky Mountain National Park in Colorado.

to forest structure (age, tree size, and species composition) and air pollutants than climate over recent decades. Nonetheless, mortality of some eastern tree groups is related to rising temperature[18] and is expected to increase as climate warms.[19]

Future disturbance rates in forests will depend on changes in the frequency of extreme events as well as the underlying changes in average climate conditions.[9,20] Of particular concern is the potential for increased forest disturbance as the result of drought accompanied with warmer temperatures, which can cause both wildfire and tree death. Temperatures have generally been increasing and are projected to increase in the future (see Ch. 2: Our Changing Climate). Therefore, although it is difficult to predict trends in future extreme events,[21] there is a high degree of confidence that future droughts will be accompanied by generally warmer conditions. Trees die faster when drought is accompanied by higher temperatures, so short droughts can trigger mortality if temperatures are higher.[22] Short droughts occur more frequently than long droughts. Consequently, a direct effect of rising temperatures may be substantially greater tree mortality even with no change in drought frequency.[22]

Given strong relationships between climate and fire, even when modified by land use and management, such as fuel treatments (Figure 7.2), projected climate changes suggest that western forests in the United States will be increasingly affected by large and intense fires that occur more frequently.[16,23,24,25] These impacts are compounded by a legacy of fire suppression that has resulted in many U.S. forests becoming increasingly dense.[26] Eastern forests are less likely to experience immediate increases in wildfire, unless a point is reached at which rising temperatures combine with seasonal dry periods, more protracted drought, and/or insect outbreaks to trigger wildfires – conditions that have been seen in Florida (see Ch. 17: Southeast).

Rising temperatures and CO_2 levels can increase growth or alter migration of some tree species;[1,27] however, the relationship between rising temperature and mortality is complex. For example, most functional groups show a decrease in mortality with higher summer temperatures (with the exception of northern groups), whereas warmer winters are correlated with higher mortality for some functional groups.[18] Tree mortality is often the result of a combination of many factors; thus increases in pollutants, droughts, and wildfires will increase the probability of a tree dying (Figure 7.3). Under projected climate conditions, rising temperatures could work together with forest stand characteristics and these other stressors to increase mortality. Recent die-offs have been more severe than projected.[11,14] As temperatures increase to levels projected for mid-century and beyond, eastern forests may be at risk of die-off.[19] New evidence indicates that most tree species can endure only limited abnormal water stress, reinforcing the idea that trees in wetter as well as semiarid forests are vulnerable to drought-induced mortality under warming climates.[28]

Effectiveness of Forest Management in Reducing Wildfire Risk

Figure 7.2. Forest management that selectively removes trees to reduce fire risk, among other objectives (a practice referred to as "fuel treatments"), can maintain uneven-aged forest structure and create small openings in the forest. Under some conditions, this practice can help prevent large wildfires from spreading. Photo shows the effectiveness of fuel treatments in Arizona's 2002 Rodeo-Chediski fire, which burned more than 400 square miles – at the time the worst fire in state history. Unburned area (left) had been managed with a treatment that removed commercial timber, thinned non-commercial-sized trees, and followed with prescribed fire in 1999. The right side of the photo shows burned area on the untreated slope below Limestone Ridge. (Photo credit: Jim Youtz, U.S. Forest Service).

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Climate change is contributing to increases in wildfires across the western U.S. and Alaska.

Forest Vulnerability to Changing Climate

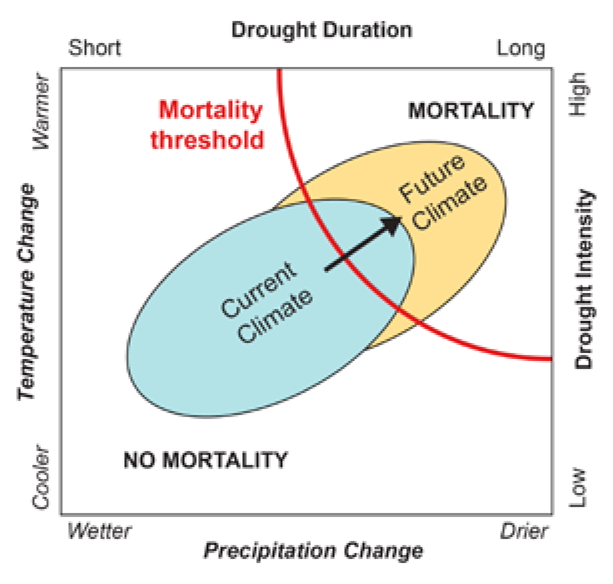

Figure 7.3. The figure shows a conceptual climate envelope analysis of forest vulnerability under current and projected future ranges of variability in climate parameters (temperature and precipitation, or alternatively drought duration and intensity). Climate models project increasing temperatures across the U.S. in coming decades, but a range of increasing or decreasing precipitation depending on region. Episodic droughts (where evaporation far exceeds precipitation) are also expected to increase in duration and/or intensity (see Ch. 2: Our Changing Climate). The overall result will be increased vulnerability of forests to periodic widespread regional mortality events resulting from trees exceeding their physiological stress thresholds.[11] (Figure source: Allen et al. 2010[11]).

Large-scale die-off and wildfire disturbance events could have potential impacts occurring at local and regional scales for timber production, flooding and erosion risks, other changes in water budgets, biogeochemical changes including carbon storage, and aesthetics.[29,30,31] Rising disturbance rates can increase harvested wood output and potentially lower prices; however, higher disturbance rates could make future forest investments more risky (Figure 7.4). Western forests could also lose substantial amounts of carbon storage capacity. For example, an increase in wildfires, insect outbreaks, and droughts that are severe enough to alter soil moisture and nutrient contents can result in changes in tree density or species composition.[10]

Key Message 2: Changing Carbon Uptake

U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest CO_2 uptake.

Climate-related Effects on Trees and Forest Productivity

Forests within the United States grow across a wide range of latitudes and altitudes and occupy all but the driest regions. Current forest cover has been shaped by climate, soils, topography, disturbance frequency, and human activity. Forest growth appears to be slowly accelerating (less than 1% per decade) in regions where tree growth is limited by low temperatures and short growing seasons that are gradually being altered by climate change (for species shifts, see Ch. 8: Ecosystems).[32] Forest carbon storage appears to be increasing both globally and within the United States.[33] Continental-scale satellite measurements document a lengthening growing season in the last thirty years, yet earlier spring growth may be negated by mid-summer drought.[34]

By the end of the century, snowmelt may occur a month earlier, but forest drought stress could increase by two months in the Rocky Mountain forests.[35] In the eastern United States, elevated CO_2 and temperature may increase forest growth and potentially carbon storage if sufficient water is available.[1,31,36] Despite recent increases in forest growth, future net forest carbon storage is expected to decline due to accelerating mortality and disturbance.

Forests can be a Source – or a Sink – for Carbon

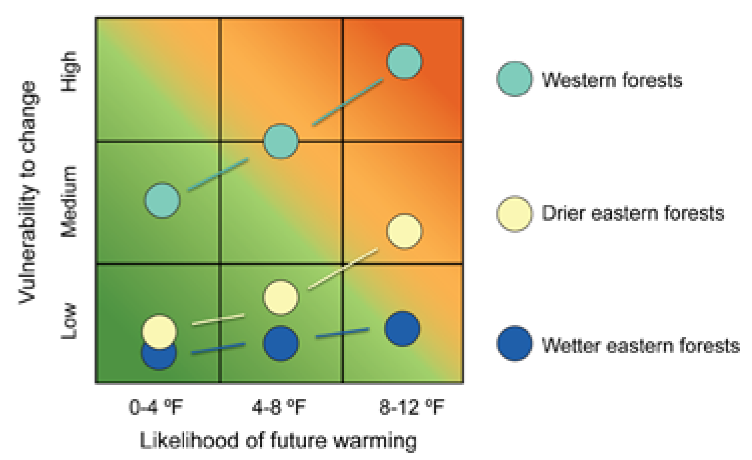

Figure 7.4. Relative vulnerability of different forest regions to climate change is illustrated in this conceptual risk analysis diagram. Forest carbon exchange is the difference between carbon captured in photosynthesis and carbon released by respiration of vegetation and soils. Both photosynthesis and respiration are generally accelerated by higher temperatures, and slowed by water deficits, but the relative strengths of these controls are highly variable. Western forests are inherently limited by evaporation that exceeds precipitation during much of the growing season. Xeric (drier) eastern forests grow on shallow, coarse textured soils and experience water deficits during long periods without rain. Mesic (wetter) eastern forests experience severe water deficits only for relatively brief periods in abnormally dry years so the carbon exchanges are more controlled by temperature fluctuations. (Figure source: adapted from Vose et al. 2012[1]).

Forest Carbon Sequestration and Carbon Management

From the onset of European settlement to the start of the last century, changes in U.S. forest cover due to expansion of agriculture, tree harvests, and settlements resulted in net emissions of carbon.[37,38] More recently, with forests reoccupying land previously used for agriculture, technological advances in harvesting, and changes in forest management, U.S. forests and associated wood products now serve as a substantial carbon sink, capturing and storing more than 227.6 million tons of carbon per year.[3] The amount of carbon taken up by U.S. land is dominated by forests (Figure 7.5), which have annually absorbed 7% to 24% of fossil fuel carbon dioxide (CO_2) emissions in the U.S. over the past two decades. The best estimate is that forests and wood products stored about 16% (833 teragrams, or 918.2 million short tons, of CO_2 equivalent in 2011) of all the CO_2 emitted annually by fossil fuel burning in the United States (see also "Estimating the U.S. Carbon Sink" in Ch. 15: Biogeochemical Cycles).[3]

Forest Growth Provides an Important Carbon Sink

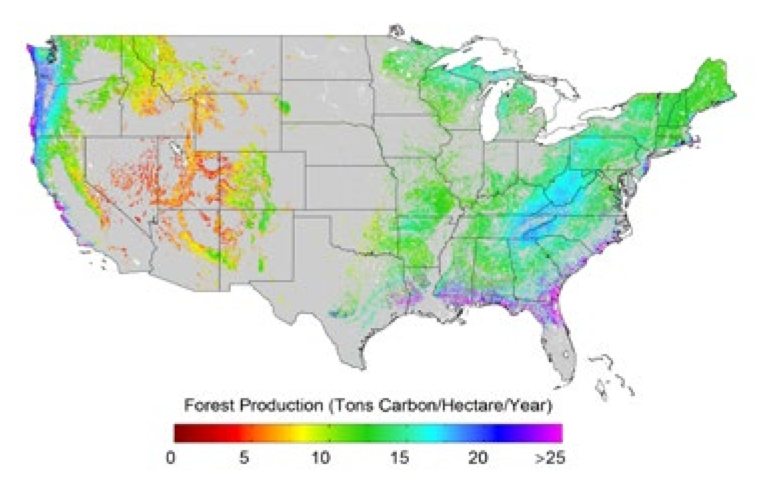

Figure 7.5. Forests are the largest component of the U.S. carbon sink, but growth rates of forests vary widely across the country. Well-watered forests of the Pacific Coast and Southeast absorb considerably more than the arid southwestern forests or the colder northeastern forests. Climate change and disturbance rates, combined with current societal trends regarding land use and forest management, are projected to reduce forest CO_2 uptake in the coming decades.[1] Figure shows average forest growth as measured by net primary production from 2000 to 2006. (Figure source: adapted from Running et al. 2004[46]).

The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (see Figures 7.3 and 7.4), as well as shifts in tree species, ranges, and productivity (Figure 7.6).[19,38] Economic factors will affect any future carbon cycle of forests, as the age class and condition of forests are affected by the acceleration of harvesting,[39,40] land-use changes such as urbanization,[41] changes in forest types,[42] and bioenergy development.[41,43,44,45]

Efforts in forestry to reduce atmospheric CO_2 levels have focused on forest management and forest product use. Forest management strategies include land-use change to increase forest area (afforestation) and/or to avoid deforestation and optimizing carbon management in existing forests. Forest product-use strategies include the use of wood wherever possible as a structural substitute for steel and concrete, which require more carbon emissions to produce.[38] The carbon emissions offset from using wood rather than alternate materials for a range of applications can be two or more times the carbon content of the product.[47]

In the U.S., afforestation (active establishment or planting of forests) has the potential to capture and store a maximum of 225 million tons of additional carbon per year from 2010 to 2110[39,48] (an amount almost equivalent to the current annual carbon storage in forests). Tree and shrub encroachment into grasslands, rangelands, and savannas provides a large potential carbon sink that could exceed half of what existing U.S. forests capture and store annually.[48]

Expansion of urban and suburban areas is responsible for much of the current and expected loss of U.S. forestland, although these human-dominated areas often have extensive tree cover and potential carbon storage (see also Ch. 13: Land Use & Land Cover Change).[41] In addition, the increasing prevalence of extreme conditions that encourage wildfires can convert some forests to shrublands and meadows[25] or permanently reduce the amount of carbon stored in existing forests if fires occur more frequently.[49]

Carbon management on existing forests can include practices that increase forest growth, such as fertilization, irrigation, switching to fast-growing planting stock, shorter rotations, and weed, disease, and insect control.[50] In addition, forest management can increase average forest carbon stocks by increasing the interval between harvests, by decreasing harvest intensity, or by focused density/species management.[4,51] Since 1990, CO_2 emissions from wildland forest fires in the lower 48 United States have averaged about 67 million tons of carbon per year.[52,53] While forest management practices can reduce on-site carbon stocks, they may also help reduce future climate change by providing feedstock material for bioenergy production and by possibly avoiding future, potentially larger, wildfire emissions through fuel treatments (Figure 7.2).[1]

Forests and Carbon

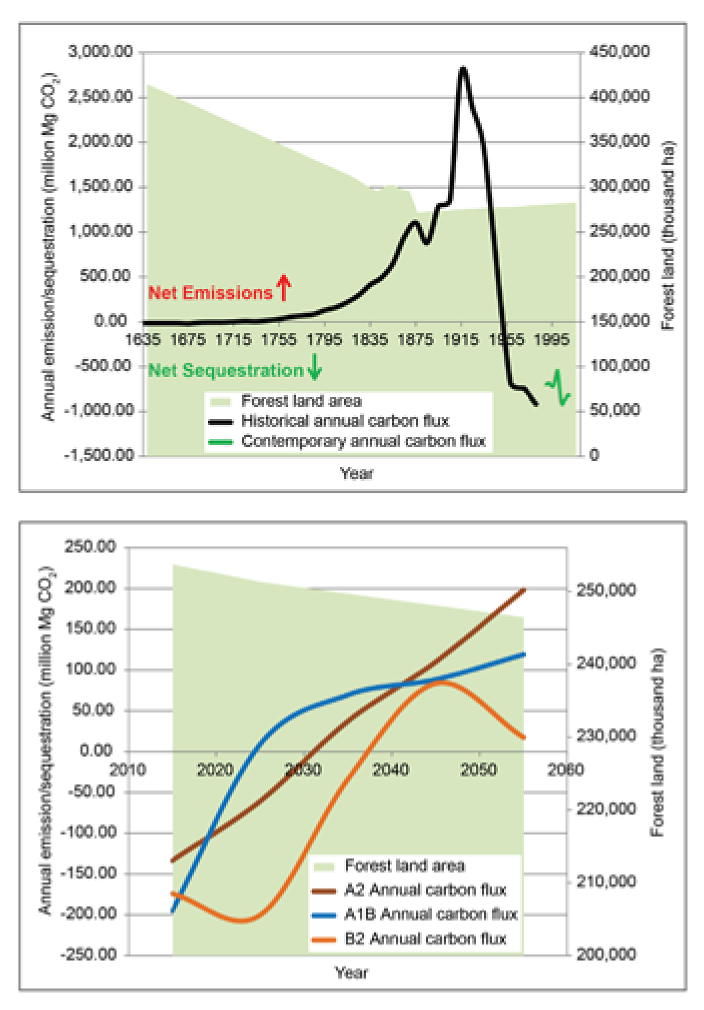

Figure 7.6. Historical, current, and projected annual rates of forest ecosystem and harvested wood product CO_2 net emissions/sequestration in the U.S. from 1635 to 2055. In the top panel, the change in the historical annual carbon emissions (black line) in the early 1900s corresponds to the peak in the transformation of large parts of the U.S. from forested land to agricultural land uses. Green shading shows this decline in forest land area. In the bottom panel, future projections shown under higher (A2) and lower (B2 and A1B) emissions scenarios show forests as carbon sources (due to loss of forest area and accelerating disturbance rates) rather than sinks in the latter half of this century. The A1B scenario assumes similar emissions to the A2 scenario used in this report through 2050, and a slow decline thereafter. (Data from Birdsey 2006;[37] USFS 2012;[41] EPA 2013.[53])

Key Message 3: Bioenergy Potential

Bioenergy could emerge as a new market for wood and could aid in the restoration of forests killed by drought, insects, and fire.

Bioenergy refers to the use of plant-based material to produce energy, and comprises about 28% of the U.S. renewable energy supply (Ch. 10: Energy, Water, and Land). Forest resources potentially could produce bioenergy from 504 million acres of timberland and 91 million acres of other forested land (Figure 7.7). Bioenergy from all sources, including agricultural and forests, could theoretically supply the equivalent of up to 30% of current U.S. petroleum consumption, but only if all relevant policies were optimized.[45] The *maximum* projected potential for forest bioenergy ranges from 3% to 5% of total current U.S. energy consumption.[54]

Forest biomass energy could be one component of an overall bioenergy strategy to reduce emissions of carbon from fossil fuels,[55] while also improving water quality[56,57] and maintaining lands for timber production as an alternative to other socioeconomic options. Active biomass energy markets using wood and forest residues have emerged in the southern and northeastern United States, particularly in states that have adopted renewable fuel standards. The economic viability of using forests for bioenergy depends on regional context and circumstances, such as species type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution, and use.[58] The environmental and socioeconomic consequences of bioenergy production vary greatly with region and intensity of human management.

The potential for biomass energy to increase timber harvests has led to debates about whether forest biomass energy leads to higher carbon emissions.[44,59] The debate on biogenic emissions regulations revolves around how to account for emissions related to biomass production and use.[60] The forest carbon balance naturally changes over time and also depends on forest management scenarios. For example, utilizing natural beetle-killed forests will yield a different carbon balance than growing and harvesting a live, fast-growing plantation.

Location of Potential Forestry Biomass Resources

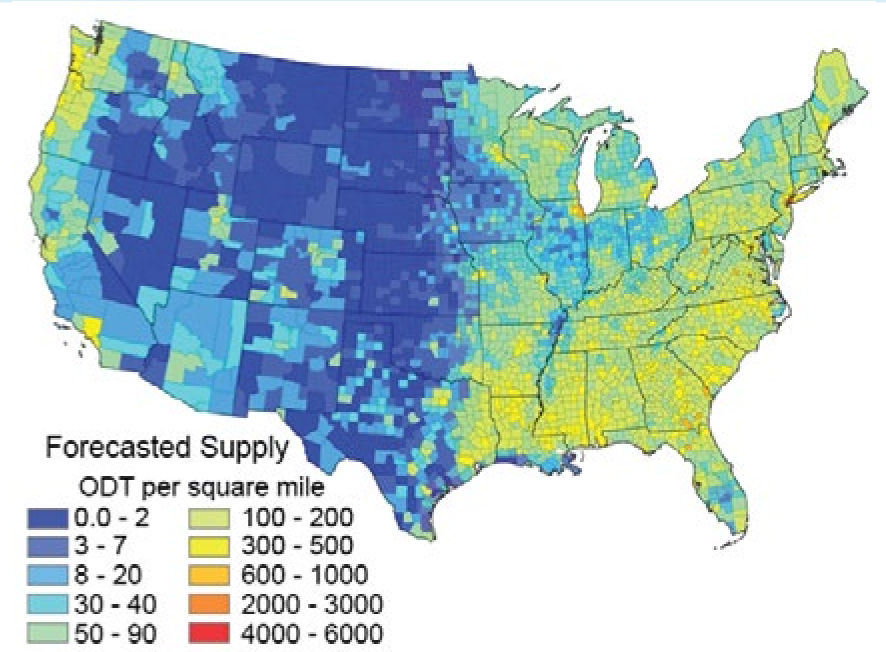

Figure 7.7. Potential forestry bioenergy resources by 2030 at $80 per dry ton of biomass based on current forest area, production rates based on aggressive management for fast-growth, and short rotation bioenergy plantations. Units are oven dry tons (ODT) per square mile at the county level, where an ODT is 2,000 pounds of biomass from which the moisture has been removed. Includes extensive material from existing forestland, such as residues, simulated thinnings, and some pulpwood for bioenergy, among other sources. (Figure source: adapted from U.S. Department of Energy 2011[45]).

Markets for energy from biomass appear to be ready to grow in response to energy pricing, policy, and demand,[44] although recent increases in the supply of natural gas have reduced the perceived urgency for new biomass projects. Further, because energy facilities typically buy the lowest quality wood at prices that rarely pay much more than cutting and hauling costs, they often require a viable saw timber market nearby to ensure an adequate, low-cost supply of material.[61] Where it is desirable to remove dead wood after disturbances to thin forests or to dispose of residues, a viable bioenergy industry could finance such activities. However, the bioenergy market has yet to be made a profitable enterprise in most U.S. regions.

Key Message 4: Influences on Management Choices

Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy.

Climate change will affect trees and forests in urban areas, the wildland-urban interface, and in rural areas. It will also challenge forest landowners managing forests for commercial products, energy development, environmental services such as watershed protection, or the conversion of forestland to developed and urban uses or agriculture. With increases in urbanization, the value of forests in and around urban areas in providing environmental services required by urban residents will increase.[41] Potentially the greatest shifts in goods and environmental services produced from forests could occur in rural areas where social and economic factors will interact with the effects of climate change at landscape scales.

Owner objectives, markets for forest products, crops and energy, the monetary value of private land, and policies governing private and public forestland all influence the actions taken to manage U.S. forestlands (56% privately owned, 44% public) (Figure 7.8). Ownership changes can bring changes in forest objectives. Among corporate owners (18% of all forestland), ownership has shifted from forest industry to investment management organizations that may or may not have active forest management as a primary objective. Non-corporate private owners, an aging demographic, manage 38% of forestland. Their primary objectives are maintaining aesthetics and the privacy that the land provides as well as preserving the land as part of their family legacy.[62]

A significant economic factor facing private forest owners is the value of their forestlands for conversion to urban or developed uses. Economic opportunities from forests include wood products, non-timber forest products, recreation activities, and in some cases, environmental services.[1,41] Less than 1% of the volume of commercial trees from U.S. forestlands is harvested annually, and 92% of this harvest comes from private forestlands.[2] Markets for wood products in the United States have been affected by increasingly competitive global markets,[63] and timber prices are not projected to increase without substantial increases in wood energy consumption or other new timber demands.[41] Urban conversions of forestland over the next 50 years could result in the loss of 16 to 31 million acres.[41] The willingness of private forest owners to actively manage forests in the face of climate change will be affected primarily by market and policy incentives, not climate change itself.

The ability of public, private, and tribal forest managers to adapt to future climate change will be enhanced by their capacity to alter management regimes relatively rapidly in the face of changing conditions. The response to climate change may be greater on private forestlands where, in the past, owners have been highly responsive to market and policy signals.[64] These landowners may be able to use existing or current forest management practices to reduce disturbance effects, increase the capture and storage of carbon, and modify plant species distributions under climate change. In addition, policy incentives, such as carbon pricing or cap and trade markets, could influence landowner choices. For human communities dependent upon forest resources, maintaining or enhancing their current resilience to change will influence their ability to respond to future stresses from climate change.[65]

On public, private, and tribal lands, management practices that can be used to reduce disturbance effects include altering tree planting and harvest strategies through species selection and timing; factoring in genetic variation; managing for reduced stand densities, which could reduce wildfire risk; reducing other stressors such as poor air quality; using forest management practices to minimize drought stress; and developing regional networks to mitigate impacts on ecosystem goods and services.[1,30,66] Legally binding regulatory requirements may constrain adaptive management where plants, animals, ecosystems, and people are responding to climate change.[67]

Lack of fine-scale information about the possible effects of climate changes on locally managed forests limits the ability of managers to weigh these risks to their forests against the economic risks of implementing forest management practices such as adaptation and/or mitigation treatments. This knowledge gap will impede the implementation of effective management on public or private forestland in the face of climate change.

Public and Private Forestlands

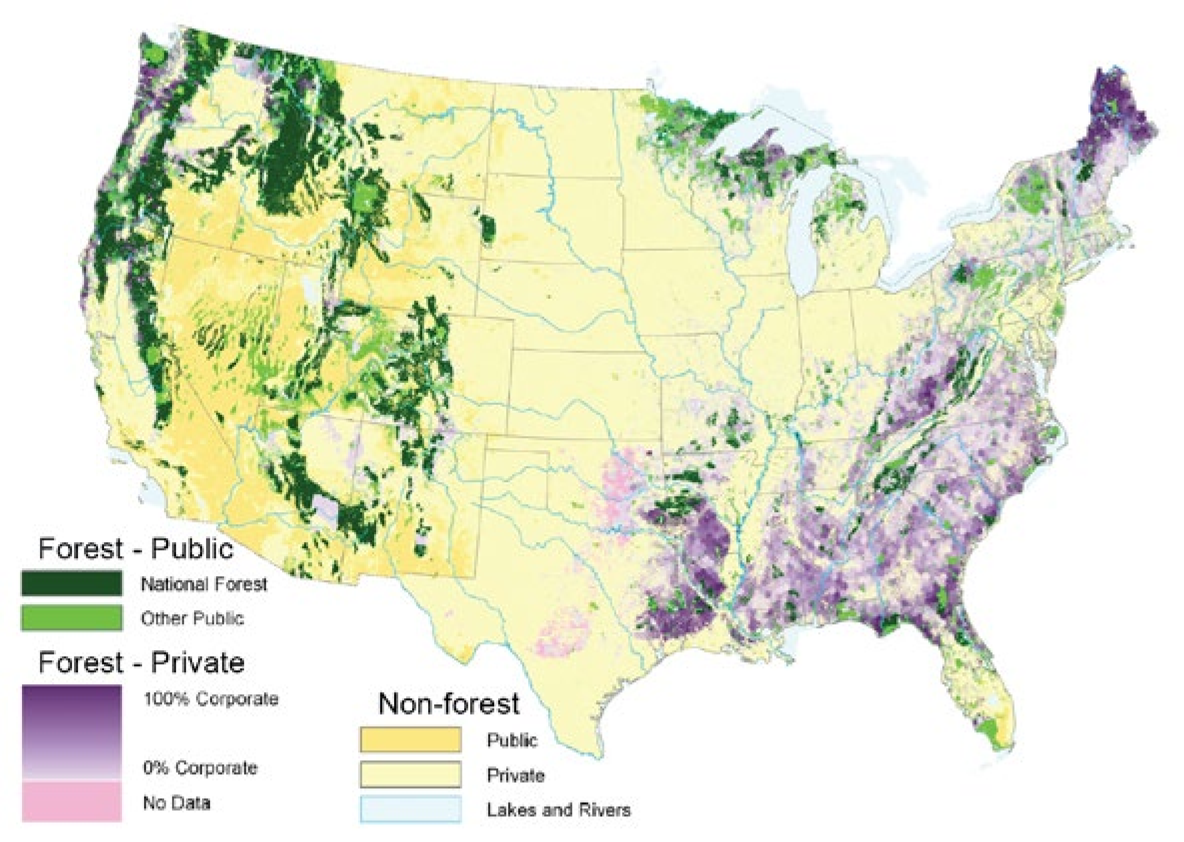

Figure 7.8. The figure shows forestland by ownership category in the contiguous U.S. in 2007.[41] Western forests are most often located on public lands, while eastern forests, especially in Maine and in the Southeast, are more often privately held. (Figure source: U.S. Forest Service 2012[41]).

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

A central component of the process was a workshop held in July 2011 by the U.S. Department of Agriculture Forest Service to guide the development of the technical input report (TIR). This session, along with numerous teleconferences, led to the foundational TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1]

The chapter authors engaged in multiple technical discussions via teleconference between January and June 2012, which included careful review of the foundational TIR and of 58 additional technical inputs provided by the public, as well as other published literature and professional judgment. Discussions were followed by expert deliberation of draft key messages by the authors and targeted consultation with additional experts by the lead author of each message.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Climate change is increasing the vulnerability of many forests to ecosystem changes and tree mortality through fire, insect infestations, drought, and disease outbreaks.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Dale et al.[8] addressed a number of climate change factors that will affect U.S. forests and how they are managed. This is supported by additional publications focused on effects of drought and by more large-scale tree die-off events,[11,22] wildfire,[16,23,25] insects and pathogens. [11,22] Other studies support the negative impact of climate change by examining the tree mortality rate due to rising temperatures,[9,11,14,15,16,17,19,22] which is projected to increase in some regions.[22]

Although it is difficult to detect a trend in disturbances because they are inherently infrequent and it is impossible to attribute an individual disturbance event to changing climate, there is nonetheless much that past events, including recent ones, reveal about expected forest changes due to future climate. Observational[17] and experimental[22] studies show strong associations between forest disturbance and extreme climatic events and/or modifications in atmospheric evaporative demand related to warmer temperature. Regarding eastern forests, there are fewer observational or experimental studies, with Dietz and Moorcroft[18] being the most comprehensive.

Pollution and stand age are the most important factors in mortality. Tree survival increases with increased temperature in some groups. However, for other tree groups survival decreases with increased temperature.[18] In addition, this study[18] needs to be considered in the context that there have been fewer severe droughts in this region. However, physiological relationships suggest that trees will generally be more susceptible to mortality under an extreme drought, especially if it is accompanied by warmer temperatures.[13,68] Consequently, it is misleading to assume that, because eastern forests have not yet experienced the types of large-scale die-off seen in the western forests, they are not vulnerable to such events if an extreme enough drought occurs. Although the effect of temperature on the rate of mortality during drought has only been shown for one species,[22] the basic physiological relationships for trees suggest that warmer temperatures will exacerbate mortality for other species as well.[13,68]

Figure 7.1: This figure uses a figure from Goetz et al. 2012[7] which uses the MODIS Global Disturbance Index (MGDI) results from 2005 to 2009 to illustrate the geographic distribution of major ecosystem disturbance types across North America (based on Mildrexler et al. 2007, 2009[6,69]). The MGDI uses remotely sensed information to assess the intensity of the disturbance. Following the occurrence of a major disturbance, there will be a reduction in Enhanced Vegetation Index (EVI) because of vegetation damage; in contrast, Land Surface Temperature (LST) will increase because more absorbed solar radiation will be converted into sensible heat as a result of the reduction in evapotranspiration from less vegetation density. MGDI takes advantage of the contrast changes in EVI and LST following a disturbance to enhance the signal to ef-

fectively detect the location and intensity of disturbances (http://www.ntsg.umt.edu/project/mgdi). Moderate severity disturbance is mapped in orange and represents a 65%-100% divergence of the current-year MODIS Global Disturbance Index value from the range of natural variability, High severity disturbance (in red) signals a divergence of over 100%.[7]

New information and remaining uncertainties

Forest disturbances have large ecosystem effects, but high interannual variability in regional fire and insect activity makes detection of trends more difficult than for changes in mean conditions.[20,21,70] Therefore, there is generally less confidence in assessment of future projections of disturbance events than for mean conditions (for example, growth under slightly warmer conditions).[21]

There are insufficient data on trends in windthrow, ice storms, hurricanes, and landslide-inducing storms to infer that these types of disturbance events are changing.

Factors affecting tree death, such as drought, warmer temperatures, and/or pests and pathogens are often interrelated, which means that isolating a single cause of mortality is rare.[11,12,13,17,22,68]

Assessment of confidence based on evidence

Very High. There is very high confidence that under projected climate changes there is high risk (high risk = high probability and high consequence) that western forests in the United States will be affected increasingly by large and intense fires that occur more frequently.[16,23,25] This is based on the strong relationships between climate and forest response, shown observationally[17] and experimentally.[22] Expected responses will increase substantially to warming and also in conjunction with other changes such as an increase in the frequency and/or severity of drought and amplification of pest and pathogen impacts. Eastern forests are less likely to experience immediate increases in wildfire unless/until a point is reached at which warmer temperatures, concurrent with seasonal dry periods or more protracted drought, trigger wildfires.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

U.S. forests and associated wood products currently absorb and store the equivalent of about 16% of all carbon dioxide (CO_2) emitted by fossil fuel burning in the U.S. each year. Climate change, combined with current societal trends in land use and forest management, is projected to reduce this rate of forest CO_2 uptake.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

A recent study[3] has shown that forests are a big sink of CO_2 nationally. However, the permanence of this carbon sink is contingent on forest disturbance rates, which are changing, and on economic conditions that may accelerate harvest of forest biomass.[56] Market response can cause changes in the carbon source/sink dynamics through shifts in forest age,[39,40] land-use changes and urbanization that reduce forested areas,[41] forest type changes,[42] and bioenergy development changing forest management.[41,43,44,45] Additionally, publications have reported that fires can convert a forest into a shrubland or meadow,[25] with frequent fires permanently reducing the carbon stock.[49]

New information and remaining uncertainties

That economic factors and societal choices will affect future carbon cycle of forests is known with certainty; the major uncertainties come from the future economic picture, accelerating disturbance rates, and societal responses to those dynamics.

Assessment of confidence based on evidence

Based on the evidence and uncertainties, confidence is **high** that climate change, combined with current societal trends regarding land use and forest management, is projected to reduce forest CO_2 uptake in the U.S. The U.S. has already seen large-scale shifts in forest cover due to interactions between forestland use and agriculture (for example, between the onset of European settlement to the present). There are competing demands for how forestland is used today. The future role of U.S. forests in the carbon cycle will be affected by climate change through changes in disturbances (Key Message 1), growth rates, and harvest demands.

Key message #3 Traceable Account

Bioenergy could emerge as a new market for wood and could aid in the restoration of forests killed by drought, insects, and fire.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Studies have shown that harvesting forest bioenergy can prevent carbon emissions[55] and replace a portion of U.S. energy consumption to help reduce future climate change. Some newer literature has explored how use of forest bioenergy can replace a portion of current U.S. energy production from oil.[20,45] Some more recent publications have reported some environmental benefits, such as improved water quality[56,57] and better management of timber lands,[45] that can result from forest bioenergy implementation.

New information and remaining uncertainties

The implications of forest product use for bioenergy depends on regional context and circumstances, such as feedstock type and prior management, land conditions, transport and storage logistics, conversion processes used to produce energy, distribution and use.[58]

The potential for biomass energy to increase forest harvests has led to debates about whether biomass energy is net carbon neutral.[59] The debate on biogenic emissions regulations revolves around how to account for emissions related to biomass production and use.[60] Deforestation contributes to atmospheric CO_2 concentration, and that contribution has been declining over time. The bioenergy contribution question is largely one of incentives for appropriate management. When forests have no value, they are burned or used inappropriately. Bioenergy can be produced in a way that provides more benefits than costs or vice versa. The market for energy from biomass appears to be ready to grow in response to energy pricing, policy, and demand; however, this industry is yet to be made a large-scale profitable enterprise in most regions of the United States.

Assessment of confidence based on evidence

High. Forest growth substantially exceeds annual harvest for normal wood and paper products, and much forest harvest residue is now unutilized. Forest bioenergy will become viable if policy and economic energy valuations make it competitive with fossil fuels.

Key message #4 Traceable Account

Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and U.S. climate change policy.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the TIR, "Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector."[1] Technical input reports (58) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The forest management response to climate change in urban areas, the wildland-urban interface, and in rural areas has been studied from varying angles. The literature on urban forests identifies the value of those forests to clean air, aesthetics, and recreation and suggests that under a changing climate, urban communities will continue to enhance their environment with trees and urban forests.[1,41] In the wildland-urban area and the rural areas, the changing composition of private forest landowners will affect the forest management response to climate change. Shifts in corporate owners to include investment organizations that may or may not have forest management as a primary objective has been described nationally.[1,2] Family forest owners are an aging demographic; one in five acres of forestland is owned by someone who is at least 75 years of age.[62] Multiple reasons for ownership are given by family forest owners, including the most commonly cited reasons of beauty/scenery, to pass land on to heirs, privacy, nature protection, and part of home/cabin. Many family forest owners feel it is necessary to keep the woods healthy but many are not familiar with forest management practices.[62] Long-term studies of the forest sector in the southern United States document the adaptive response of forest landowners to market prices as they manage to supply wood and associated products from their forests;[64] however prices are less of an incentive in other parts of the United States.[1,41] Econometric approaches have been used to explore the economic activities in the forest sector, including interactions with other sectors such as agriculture, impact of climate change, and the potential for new markets with bioenergy.[43,44] An earlier study explored the effects of globalization on forest management[63] and a newer study looked at the effect of U.S. climate change policy.[67] One of the biggest challenges is the lack of climate change information that results in inaction from many forest owners.[62]

New information and remaining uncertainties

Human concerns regarding the effects of climate change on forests and the role of adaptation and mitigation will be viewed from the perspective of the values that forests provide to human populations, including timber products, water, recreation, and aesthetic and spiritual benefits.[1] Many people, organizations, institutions, and governments influence the management of U.S. forests. Economic opportunities influence the amount and nature of private forestland (and much is known quantitatively about this dynamic) and societal values have a strong influence on how public forestland is managed. However, it remains challenging to project exactly how humans will respond to climate change in terms of forest management.

Climate change will alter known environmental and economic risks and add new risks to be addressed in the management of forests in urban areas, the wildland-urban interface, and rural areas. The capacity to manage risk varies greatly across landowners. While adaptation strategies provide a means to manage risks associated with climate change, a better understanding of risk perception by forest landowners would enhance the development and implementation of these management strategies. Identification of appropriate monitoring information and associated tools to evaluate monitoring data could facilitate risk assessment. Information and tools to assess environmental and economic risks associated with the impacts of climate change in light of specific management decisions would be informative to forestland managers and owners.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainty, there is **medium** confidence in this key message. Climate change and global and national economic events will have an integral impact on forest management, but it is uncertain to what magnitude. While forest landowners have shown the capacity to adapt to new economic conditions, potential changes in the international markets coincident with large-scale natural disturbances enhanced by climate change (fire, insects) could challenge this adaptive capacity. An important uncertainty is how people will respond to climate change in terms of forest management.

Climate Change Impacts in the United States

CHAPTER 8
ECOSYSTEMS,
BIODIVERSITY, AND ECOSYSTEM SERVICES

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8

ECOSYSTEMS,
BIODIVERSITY, AND ECOSYSTEM SERVICES

KEY MESSAGES

1. **Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.**
2. **Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.**
3. **Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.**
4. **Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.**
5. **Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.**

Climate change affects the living world, including people, through changes in ecosystems, biodiversity, and ecosystem services. Ecosystems entail all the living things in a particular area as well as the non-living things with which they interact, such as air, soil, water, and sunlight.[1] Biodiversity refers to the variety of life, including the number of species, life forms, genetic types, and habitats and biomes (which are characteristic groupings of plant and animal species found in a particular climate). Biodiversity and ecosystems produce a rich array of benefits that people depend on, including fisheries, drinking water, fertile soils for growing crops, climate regulation, inspiration, and aesthetic and cultural values.[2] These benefits are called "ecosystem services" – some of which, like food, are more easily quantified than others, such as climate regulation or cultural values. Changes in many such services are often not obvious to those who depend on them.

Ecosystem services contribute to jobs, economic growth, health, and human well-being. Although we interact with ecosystems and ecosystem services every day, their linkage to climate change can be elusive because they are influenced by so many additional entangled factors.[3] Ecosystem perturbations driven by climate change have direct human impacts, including reduced water supply and quality, the loss of iconic species and landscapes, distorted rhythms of nature, and the potential for extreme events to overwhelm the regulating services of ecosystems. Even with these well-documented ecosystem impacts, it is often difficult to quantify human vulnerability that results from shifts in ecosystem processes and services. For example, although it is more straightforward to predict how precipitation will change water flow, it is much harder to pinpoint which farms, cities, and habitats will be at risk of running out of water, and even more difficult to say how people will be affected by the loss of a favorite fishing spot or a wildflower that no longer blooms in the region. A better understanding of how a range of ecosystem responses affects people – from altered water flows to the loss of wildflowers – will help to inform the management of ecosystems in a way that promotes resilience to climate change.

Forests absorb carbon dioxide and provide many other ecosystem services, such as purifying water and providing recreational opportunities.

Key Message 1: Water

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

Climate-driven factors that control water availability and quality are moderated by ecosystems. Land-based ecosystems regulate the water cycle and are the source of sediment and other materials that make their way to aquatic ecosystems (streams, rivers, lakes, estuaries, oceans, groundwater). Aquatic ecosystems provide the critically important services of storing water, regulating water quality, supporting fisheries, providing recreation, and carrying water and materials downstream (Ch. 25: Coasts). Humans utilize, on average, the equivalent of more than 40% of renewable supplies of freshwater in more than 25% of all U.S. watersheds.[4] Freshwater withdrawals are even higher in the arid Southwest, where the equivalent of 76% of all renewable freshwater is appropriated by people.[5] In that region, climate change has likely decreased and altered the timing of streamflow due to reduced snowpack and lower precipitation in spring, although the precipitation trends are weak due to large year-to-year variability, as well as geographic variation in the patterns (Ch. 3: Water; Ch. 20: Southwest).[6] Depriving ecosystems of water reduces their ability to provide water to people as well as for aquatic plant and animal habitat (see Figure 8.1).

Habitat loss and local extinctions of fish and other aquatic species are projected from the combined effects of increased water withdrawal and climate change.[7] In the U.S., 47% of trout habitat in the interior West would be lost by 2080 under a scenario (A1B) that assumes similar emissions to the A2 scenario used in this report (Ch. 1: Overview, Ch. 2: Our Changing Climate) through 2050, and a slow decline thereafter.[8]

Across the entire U.S., precipitation amounts and intensity and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC) (Ch. 3: Water).[9] At high concentrations, nutrients that are required for life (such as nitrogen and phosphorus) can become pollutants and can promote excessive phytoplankton growth – a process known as eutrophication. Currently, many U.S. lakes and rivers are polluted (have concentrations above government standards) by excessive nitrogen, phosphorus, or sediment. There are well-established links among fertilizer use, nutrient pollution, and river discharge, and many studies show that recent increases in rainfall in several regions of the United States have led to higher nitrogen amounts carried by rivers (Northeast,[10,11] California,[12] and Mississippi Basin[13,14]). Over the past 50 years, due to both climate and land-use change, the Mississippi Basin is yielding an additional 32 million acre-feet of water each year – equivalent to four Hudson Rivers – laden with materials washed from its farmlands.[15] This flows into the Gulf of Mexico, which is the site of the nation's largest hypoxic (low oxygen) "dead" zone.[4] The majority of U.S. estuaries are moderately to highly eutrophic.[16]

Links between discharge and sediment transport are well established,[17] and cost estimates for in-stream and off-stream damages from soil erosion range from $2.1 to $10 billion per year.[18,19] These estimates include costs associated with damages to, or losses of, recreation, water storage, navigation, commercial fishing, and property, but do not include costs of biological impacts.[18] Sediment transport, with accompanying nutrients, can play a positive role in the shoreline dynamics of coastlines and the life cycles of coastal and marine plants and animals. However, many commercially and recreationally important fish species such as salmon and trout that lay their eggs in the gravel at the edges of streams are especially sensitive to elevated sediment fluxes in rivers.[20] Sediment loading in lakes has been shown to have substantial detrimental effects on fish population sizes, community composition, and biodiversity.[21]

Dissolved organic carbon (DOC) fluxes to rivers and lakes are strongly driven by precipitation;[22] thus in many regions where precipitation is expected to increase, DOC loading will also increase. Dissolved organic carbon is the substance that gives many rivers and lakes a brown, tea-colored look. Precipitation-driven increases in DOC concentration not only increase the cost of water treatment for municipal use,[23] but also alter the ability of sunlight to act as nature's water treatment plant. For example, *Cryptosporidium*, a pathogen potentially lethal to the elderly, babies, and people with compromised immune systems, is present in 17% of drinking water supplies sampled


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in the United States.[24] This pathogen is inactivated by doses of ultraviolet (UV) light equivalent to less than a day of sun exposure.[25] Similarly, UV exposures reduce fungal parasites that infect *Daphnia*, a keystone aquatic grazer and food source for fish.[26] Increasing DOC concentrations may thus reduce the ability of sunlight to regulate these UV-sensitive parasites.

Few studies have projected the impacts of climate change on nitrogen, phosphorus, sediment, or DOC transport from the land to rivers. However, given the tight link between river discharge and all of these potential pollutants, areas of the United States that are projected to see increases in precipitation, and increases in intense rainfalls, like the Northeast, Midwest, and mountainous West,[27] will also see increases in excess nutrients, DOC, and sediments transported to rivers. One of the few future projections available suggests that downstream and coastal impacts of increased nitrogen inputs could be profound for the Mississippi Basin. Under a scenario in which atmospheric CO_2 reaches double pre-industrial levels, a 20% increase in river discharge is expected to lead to higher nitrogen loads and a 50% increase in algae growth in the Gulf of Mexico, a 30% to 60% decrease in deep-water dissolved oxygen concentration, and an expansion of the dead zone.[28] A recent comprehensive assessment[10] shows that, while climate is an important driver, nitrogen carried by rivers to the oceans is most strongly driven by fertilizer inputs to the land. Therefore, in the highly productive agricultural systems of the Mississippi Basin, the ultimate impact of more precipitation on the expansion of the dead zone will depend on agricultural management practices in the Basin.[14,29]

Rising air temperatures can also lead to declines in water quality through a different set of processes. Some large lakes, including the Great Lakes, are warming rapidly.[30] Warmer surface waters can stimulate blooms of harmful algae in both lakes and coastal oceans,[9] which may include toxic cyanobacteria that are favored at higher temperatures.[31] Harmful algal blooms, which are caused by many factors, including climate change, exact a cost in freshwater degradation of approximately $2.2 billion annually in the United States alone.[32]

Water Supplies Projected to Decline

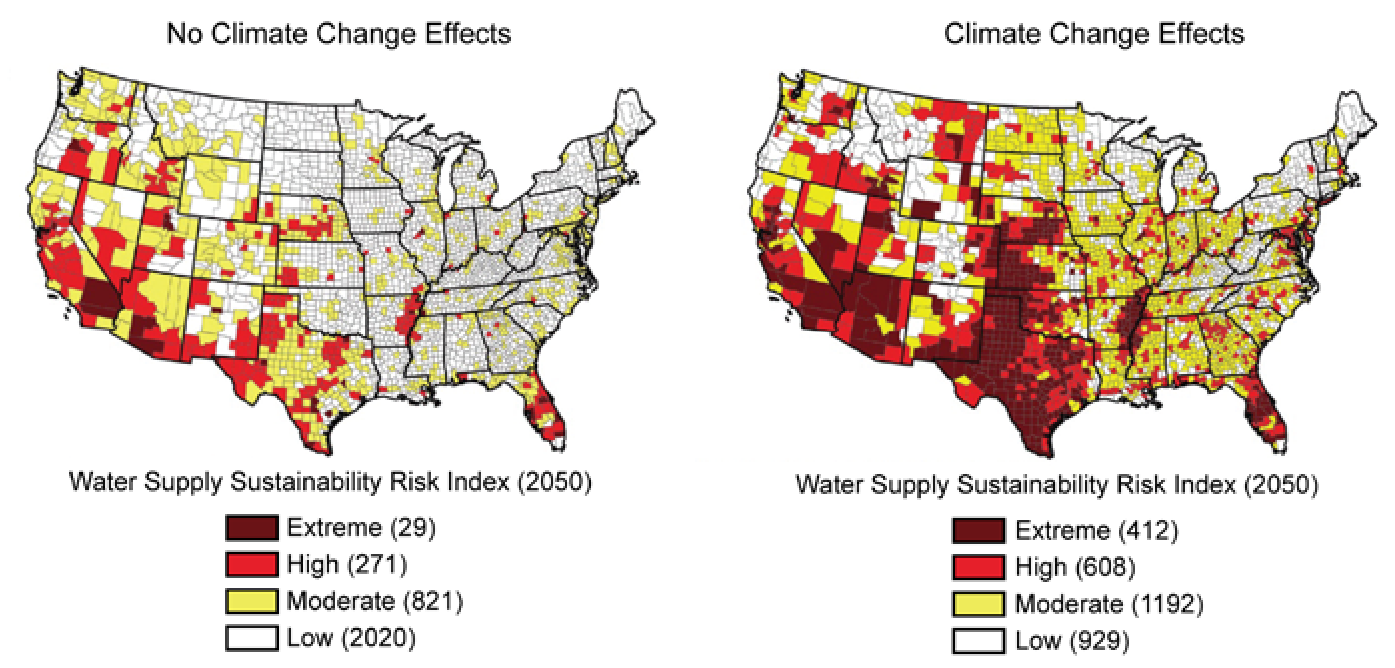

Figure 8.1. Climate change is projected to reduce the ability of ecosystems to supply water in some parts of the country. This is true in areas where precipitation is projected to decline, and even in some areas where precipitation is expected to increase. Compared to 10% of counties today, by 2050, 32% of counties will be at high or extreme risk of water shortages. Projections assume continued increases in greenhouse gas emissions through 2050 and a slow decline thereafter (A1B scenario). Numbers in parentheses indicate number of counties in each category. (Reprinted with permission from Roy et al., 2012.[27] Copyright 2012 American Chemical Society).

The Aftermath of Hurricanes

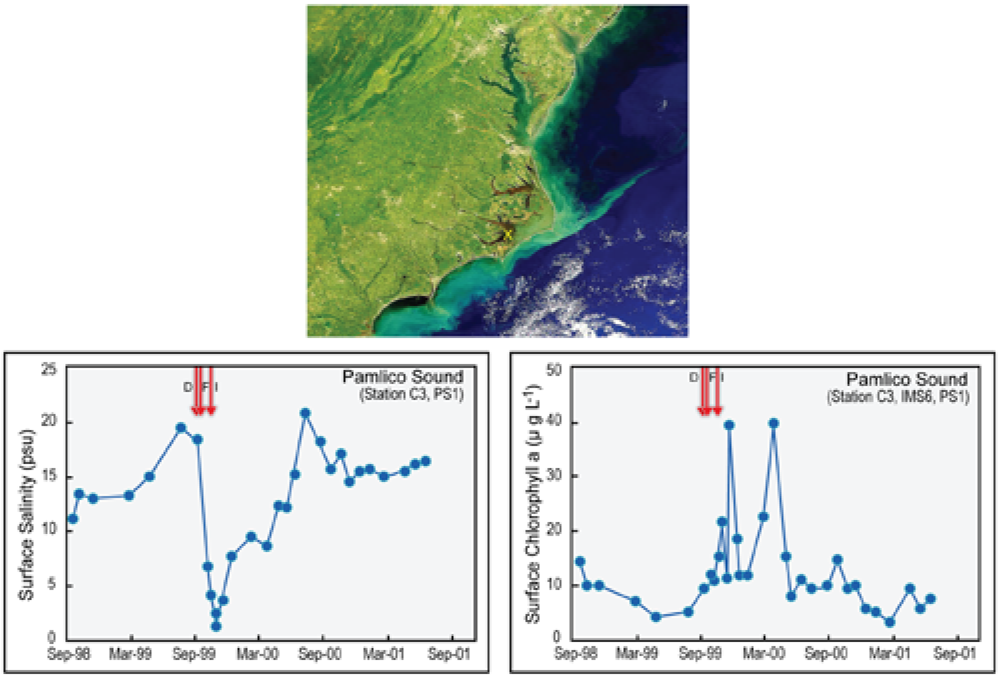

Figure 8.2. Hurricanes illustrate the links among precipitation, discharge and nutrient loading to coastal waters. Hurricanes bring intense rainfall to coastal regions, and ensuing runoff leads to blooms of algae. These blooms contribute to dead zone formation after they die and decompose. Photo above shows Pamlico Sound, North Carolina, after Hurricane Floyd. Note light green area off the coast, which is new algae growth. The graph on the left shows a steep drop in salinity of ocean water due to the large influx of freshwater from rain after a series of hurricanes. Red arrows indicate Hurricanes Dennis, Floyd, and Irene, which hit sequentially during the 1999 hurricane season. The graph on the right shows a steep rise in the amount of surface chlorophyll after these hurricanes, largely due to increased algae growth. (Figure source: (top) NASA SeaWiFS; (bottom) Paerl et al. 2003[33]).

Key Message 2: Extreme Events

Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.

Ecosystems play an important role in "buffering" the effects of extreme climate conditions (floods, wildfires, tornadoes, hurricanes) on the movement of materials and the flow of energy through the environment.[34] Climate change and human modifications often increase the vulnerability of ecosystems and landscapes to damage from extreme events while at the same time reducing their natural capacity to modulate the impacts of such events. Salt marshes, reefs, mangrove forests, and barrier islands provide an ecosystem service of defending coastal ecosystems and infrastructure against storm surges.[35] Losses of these natural features – from coastal development, erosion, and sea level rise – render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (Ch. 25: Coasts).[36] Floodplain wetlands, although greatly reduced from their historical extent, provide an ecosystem service of absorbing floodwaters and reducing the impact of high flows on river-margin lands. In the Northeast, even a small sea level rise (1.6 feet) would dramatically increase the numbers of people (47% increase) and property loss (73% increase) affected by storm surge in Long Island compared to present day storm surge impacts.[37] Extreme weather events that produce sudden increases in water flow and the materials it carries can decrease the natural capacity of ecosystems to process pollutants, both by reducing the amount of time water is in contact with reactive sites and by removing or harming the plants and microbes that remove the pollutants.[36]

Warming and, in some areas, decreased precipitation (along with past forest fire suppression practices) have increased the risk of fires exceeding historical size, resulting in unprecedented social and economic challenges. Large fires put people living in the wildland-urban interface at risk for health problems and property loss. In 2011 alone, more than 8 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 billion.[38]

Key Message 3: Plants and Animals

Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.

Vegetation model projections suggest that much of the United States will experience changes in the composition of species characteristic of specific areas. Studies applying different models for a range of future climates project biome changes for about 5% to 20% of the land area of the U.S. by 2100.[4,39] Many major changes, particularly in the western states and Alaska, will in part be driven by increases in fire frequency and severity. For example, the average time between fires in the Yellowstone National Park ecosystem is projected to decrease from 100 to 300 years to less than 30 years, potentially causing coniferous (pine, spruce, etc.) forests to be replaced by woodlands and grasslands.[40] Warming has also led to novel wildfire occurrence in ecosystems where it has been absent in recent history, such as arctic Alaska and the southwestern deserts where new fires are fueled by non-native annual grasses (Ch. 20: Southwest; Ch. 22: Alaska). Extreme weather conditions linked to sea ice decline in 2007 led to the ignition of the Anaktuvuk River Fire, which burned more than 380 square miles of arctic tundra that had not been disturbed by fire for more than 3,000 years.[41] This one fire (which burned deeply into organic peat soils) released enough carbon to the atmosphere to offset all of the carbon taken up by the entire arctic tundra biome over the past quarter-century.[42]

In addition to shifts in species assemblages, there will also be changes in species distributions. In recent decades, in both land and aquatic environments, plants and animals have moved to higher elevations at a median rate of 36 feet (0.011 kilometers) per decade, and to higher latitudes at a median rate of 10.5 miles (16.9 kilometers) per decade.[43] As the climate continues to change, models and long-term studies project even greater shifts in species ranges.[44] However, many species may not be able to keep pace with climate change for several reasons, for example because their seeds do not disperse widely or because they have limited mobility, thus leading, in some places, to local extinctions of both plants and animals. Both range shifts and local extinctions will, in many places, lead to large changes in the mix of plants and animals present in the local ecosystem, resulting in new communities that bear little resemblance to those of today.[4,8,45,46]

Some of the most obvious changes in the landscape are occurring at the boundaries between biomes. These include shifts in the latitude and elevation of the boreal (northern) forest/tundra boundary in Alaska;[47] elevation shifts of the boreal and subalpine forest/tundra boundary in the Sierra Nevada, California;[48] an elevation shift of the temperate broadleaf/conifer boundary in the Green Mountains, Vermont,[49] the shift of temperate the shrubland/conifer forest boundary in Bandelier National Monument, New Mexico,[50] and upslope shifts of the temperate mixed forest/conifer boundary in Southern California.[51] All of these are consistent with recent climatic trends and represent visible changes, like tundra switching to forest, or conifer forest switching to broadleaf forest or even to shrubland.

As temperatures rise and precipitation patterns change, many fish species (such as salmon, trout, whitefish, and char) will be lost from lower-elevation streams, including a projected loss of 47% of habitat for all trout species in the western U.S. by 2080.[8] Similarly, in the oceans, transitions from cold-water fish communities to warm-water communities have occurred in commercially important harvest areas,[52] with new industries developing in response to the arrival of new species.[53] Also, warm surface waters are driving some fish species to deeper waters.[54,55]

Warming is likely to increase the ranges of several invasive plant species in the United States,[56] increase the probability of establishment of invasive plant species in boreal forests in south-central Alaska, including the Kenai Peninsula,[57] and expand the range of the hemlock wooly adelgid, an insect that has killed many eastern hemlocks in recent years.[58] Invasive species costs to the U.S. economy are estimated at $120 billion per year,[59] including substantial impacts on ecosystem services. For instance, the yellow star-thistle, a wildland pest which is predicted to thrive with increased atmospheric CO_2,[60] currently costs California ranchers and farmers $17 million in forage and control efforts[61] and $75 million in water losses.[62] Iconic desert species such as saguaro cactus are damaged or killed by fires fueled by non-native grasses, leading to a large-scale transformation of desert shrubland into grassland in many of the familiar landscapes of the American West.[63] Bark beetles have infested extensive areas of the western United States and Canada, killing stands of temperate and boreal conifer forest across areas greater than any other outbreak in the last 125 years.[64] Climate change has been a major causal factor, with higher temperatures allowing more beetles to survive winter, complete two life cycles in a season rather than one, and to move to higher elevations and latitudes.[64,65] Bark beetle outbreaks in the Greater Yellowstone Ecosystem are occurring in habitats where outbreaks either did not previously occur or were limited in scale.[66]

It is important to realize that climate change is linked to far more dramatic changes than simply altering species' life cycles or shifting their ranges. Several species have exhibited population declines linked to climate change, with some declines so severe that species are threatened with extinction.[67] Perhaps the most striking impact of climate change is its effect on iconic species such as the polar bear, the ringed seal, and coral species (Ch. 22: Alaska; Ch. 24: Oceans). In 2008, the polar bear (*Ursus maritimus*) was listed as a threatened species, with the primary cause of its decline attributed to climate change.[68] In 2012, NOAA determined that four subspecies of the ringed seal (*Phoca hispida*) were threatened or endangered, with the primary threat being climate change.[69]

Key Message 4: Seasonal Patterns

Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

The effect of climate change on phenology – the pattern of seasonal life cycle events in plants and animals, such as timing of leaf-out, blooming, hibernation, and migration – has been called a "globally coherent fingerprint of climate change impacts" on plants and animals.[70] Observed long-term trends towards shorter, milder winters and earlier spring thaws are altering the timing of critical spring events such as bud burst and emergence from overwintering. This can cause plants and animals to be so out of phase with their natural phenology that outbreaks of pests occur, or species cannot find food at the time they emerge.

Recent studies have documented an advance in the timing of springtime phenological events across species in response to increased temperatures.[71] Long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures[72] and by 1.5 days per decade earlier in the western United States.[73] Other multi-decadal studies for plant species have documented similar trends for early flowering.[74,75] In addition, plant-pollinator relationships may be disrupted by changes in nectar and pollen availability, as the timing of bloom shifts in response to temperature and precipitation.[76,77]

As spring is advancing and fall is being delayed in response to regional changes in climate,[78] the growing season is lengthening. A longer growing season will benefit some crops and natural species, but there may be a timing mismatch between the microbial activity that makes nutrients available in the soil and the readiness of plants to take up those nutrients for growth.[78,79] Where plant phenology is driven by day length, an advance in spring may exacerbate this mismatch, causing available nutrients to be leached out of the soil rather than absorbed and recycled by plants.[80] Longer growing seasons also exacerbate human allergies. For example, a longer fall allows for bigger ragweed plants that produce more pollen later into the fall (see also Ch. 9: Health).[81]

Changes in the timing of springtime bird migrations are well-recognized biological responses to warming, and have been documented in the western,[82] midwestern,[83] and eastern United States.[84,85] Some migratory birds now arrive too late for the peak of food resources at breeding grounds because temperatures at wintering grounds are changing more slowly than at spring breeding grounds.[86]

In a 34-year study of an Alaskan creek, young pink salmon (*Oncorhynchus gorbuscha*) migrated to the sea increasingly earlier over time.[87] In Alaska, warmer springs have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou (*Rangifer tarandus*).

Key Message 5: Adaptation

Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.

Adaptation in the context of biodiversity and natural resource management is fundamentally about managing change, which is an inherent property of natural ecosystems.[4,88,89] One strategy – adaptive management, which is a structured process of flexible decision-making under uncertainty that incorporates learning from management outcomes – has received renewed attention as a tool for helping resource managers make decisions relevant to whole systems in response to climate change.[89,90] Other strategies tinclude assessments of vulnerability and impacts,[91] and scenario planning,[92] that can be assembled into a general planning process that is flexible and iterative.

Guidance on adaptation planning for conservation has proliferated at the federal[92,93,94] and state levels,[95] and often emphasizes cooperation between scientists and managers.[94,96,97] Ecosystem-based adaptation[98,99] uses "biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change."[99] An example is the explicit use of storm-buffering coastal wetlands or mangroves rather than built infrastructure like seawalls or levies to protect coastal regions (Ch. 25: Coasts).[100] An additional example is the use of wildlife corridors to connect fragmented wildlife habitat.[101]

Adaptation strategies to protect biodiversity include: 1) habitat manipulation, 2) conserving populations with higher genetic diversity or more flexible behaviors or morphologies, 3) replanting with species or ecotypes that are better suited for future climates, 4) managed relocation (sometimes referred to as assisted migration) to help move species and populations from current locations to those areas expected to become more suitable in the future, and 5) offsite conservation such as seed banking, biobanking, and captive breeding.[92,94,96,97,102,103] Additional approaches focus on identifying and protecting features that are important for biodiversity and are less likely to be altered by climate change. The idea is to conserve the "stage" (the biophysical conditions that contribute to high levels of biodiversity) for whatever "actors" (species and populations) find those areas suitable in the future.[104]

One of the greatest challenges for adaptation in the face of climate change is the revision of management goals in fundamental ways. In particular, not only will climate change make it difficult to achieve existing conservation goals, it will demand that goals be critically examined and potentially altered in dramatic ways.[102,105] Climate changes can also severely diminish the effectiveness of current strategies and require fresh approaches. For example, whereas establishing networks of nature reserves has been a standard approach to protecting species, fixed networks of reserve do not lend themselves to adjustments for climate change.[105] Finally, migratory species and species with complex life histories cannot be simply addressed by defining preferred habitat and making vulnerability assessments. Often it could be specific life history stages that are the weak point in the species, and it is key to identify those weak links.[106]

While there is considerable uncertainty about how climate change will play out in particular locations, proactive measures can be taken to both plan for connectivity[96,107] and to identify places or habitats that may in the future become valuable habitat as a result of climate change and vegetation shifts.[108] It is important to note that when the Endangered Species Act (ESA) was passed in 1973, climate change was not a known threat or factor and was not considered in setting recovery goals or critical habitat designations.[109] However, agencies are actively working to include climate change considerations in their ESA implementation activities.

Adaptation Planning and Implementation Framework

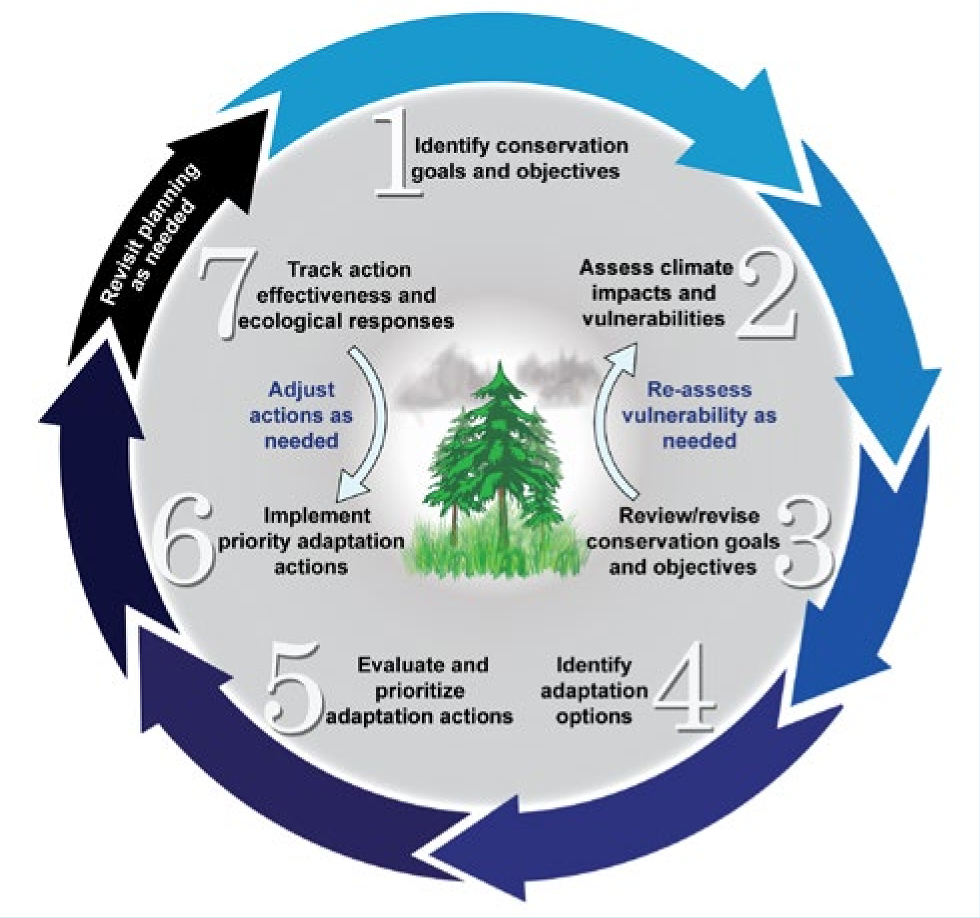

Figure 8.3. Iterative approaches to conservation planning require input and communication among many players to ensure flexibility in response to climate change. (Figure source: adapted from the National Wildlife Federation, 2013[142]).

CASE STUDY OF THE 2011 LAS CONCHAS, NEW MEXICO FIRE

In the midst of severe drought in the summer of 2011, Arizona and New Mexico suffered the largest wildfires in their recorded history, affecting more than 694,000 acres. Some rare threatened and endangered species, like the Jemez salamander, were damaged by this unusually severe fire.[110] Fires are often part of the natural disturbance regime, but if drought, poor management, and high temperatures combine, a fire can be so severe and widespread that species are damaged that otherwise might even be considered to be fire tolerant (such as spotted owls). Following the fires, heavy rainstorms led to major flooding and erosion, including at least ten debris flows. Popular recreation areas were evacuated and floods damaged the newly renovated, multi-million dollar U.S. Park Service Visitor Center at Bandelier National Monument. Sediment and ash eroded by the floods were washed downstream into the Rio Grande, which supplies 50% of the drinking water for Albuquerque, the largest city in New Mexico. Water withdrawals by the city from the Rio Grande were stopped entirely for a week and reduced for several months due to the increased cost of treatment.

These fires provide an example of how forest ecosystems, biodiversity, and ecosystem services are affected by the impacts of climate change, other environmental stresses, and past management practices. Higher temperatures, reduced snowpack, and earlier onset of springtime are leading to increases in wildfire in the western United States,[111] while extreme droughts are becoming more frequent.[112] In addition, climate change is affecting naturally occurring bark beetles: warmer winter conditions allow these pests to breed more frequently and successfully.[113,114] The dead trees left behind by bark beetles may make crown fires more likely, at least until needles fall from killed trees.[114,115] Forest management practices also have made the forests more vulnerable to catastrophic fires. In New Mexico, even-aged, second-growth forests were hit hardest because they are much denser than naturally occurring forest and consequently consume more water from the soil and increase the availability of dry above-ground fuel.

BIOLOGICAL RESPONSES TO CLIMATE CHANGE

Figure 8.4. Map of selected observed and projected biological responses to climate change across the United States. Case studies listed below correspond to observed responses (black icons on map) and projected responses (white icons on map, bold italicized statements). In general, because future climatic changes are projected to exceed those experienced in the recent past, projected biological impacts tend to be of greater magnitude than recent observed changes. Because the observations and projections presented here are not paired (that is, they are not for the same species or systems), that general difference is not illustrated. (Figure source: Staudinger et al., 2012[4]).

Continued

BIOLOGICAL RESPONSES TO CLIMATE CHANGE (CONTINUED)

1. Mussel and barnacle beds have declined or disappeared along parts of the Northwest coast due to higher temperatures and drier conditions that have compressed habitable intertidal space.[116]
2. Northern flickers arrived at breeding sites earlier in the Northwest in response to temperature changes along migration routes, and egg laying advanced by 1.15 days for every degree increase in temperature, demonstrating that this species has the capacity to adjust their phenology in response to climate change.[117]
3. Conifers in many western forests have experienced mortality rates of up to 87% from warming-induced changes in the prevalence of pests and pathogens and stress from drought.[118]
4. Butterflies that have adapted to specific oak species have not been able to colonize new tree species when climate change-induced tree migration changes local forest types, potentially hindering adaptation.[119]
5. In response to climate-related habitat change, many small mammal species have altered their elevation ranges, with lower-elevation species expanding their ranges and higher-elevation species contracting their ranges.[120]
6. ***Northern spotted owl populations in Arizona and New Mexico are projected to decline during the next century and are at high risk for extinction due to hotter, drier conditions, while the southern California population is not projected to be sensitive to future climatic changes.***[121]
7. Quaking aspen-dominated systems are experiencing declines in the western U.S. after stress due to climate-induced drought conditions during the last decade.[122]
8. Warmer and drier conditions during the early growing season in high-elevation habitats in Colorado are disrupting the timing of various flowering patterns, with potential impacts on many important plant-pollinator relationships.[77]
9. ***Population fragmentation of wolverines in the northern Cascades and Rocky Mountains is expected to increase as spring snow cover retreats over the coming century.***[123]
10. ***Cutthroat trout populations in the western U.S. are projected to decline by up to 58%, and total trout habitat in the same region is projected to decline by 47%, due to increasing temperatures, seasonal shifts in precipitation, and negative interactions with non-native species.***[8]
11. Comparisons of historical and recent first flowering dates for 178 plant species from North Dakota showed significant shifts occurred in over 40% of species examined, with the greatest changes observed during the two warmest years of the study.[75]
12. Variation in the timing and magnitude of precipitation due to climate change was found to decrease the nutritional quality of grasses, and consequently reduce weight gain of bison in the Konza Prairie in Kansas and the Tallgrass Prairie Preserve in Oklahoma.[124] Results provide insight into how climate change will affect grazer population dynamics in the future.
13. (a and b) Climatic fluctuations were found to influence mate selection and increase the probability of infidelity in birds that are normally socially monogamous, increasing the gene exchange and the likelihood of offspring survival.[125]
14. Migratory birds monitored in Minnesota over a 40-year period showed significantly earlier arrival dates, particularly in short-distance migrants, indicating that some species are capable of responding to increasing winter temperatures better than others.[126]
15. ***Up to 50% turnover in amphibian species is projected in the eastern U.S. by 2100, including the northern leopard frog, which is projected to experience poleward and elevational range shifts in response to climatic changes in the latter quarter of the century.***[127]
16. ***Studies of black ratsnake (Elaphe obsoleta) populations at different latitudes in Canada, Illinois, and Texas suggest that snake populations, particularly in the northern part of their range, could benefit from rising temperatures if there are no negative impacts on their habitat and prey.***[128]
17. Warming-induced hybridization was detected between southern and northern flying squirrels in the Great Lakes region of Ontario, Canada, and in Pennsylvania after a series of warm winters created more overlap in their habitat range, potentially acting to increase population persistence under climate change.[129]

Continued

BIOLOGICAL RESPONSES TO CLIMATE CHANGE (CONTINUED)

18. Some warm-water fishes have moved northwards, and some tropical and subtropical fishes in the northern Gulf of Mexico have increased in temperate ocean habitat.[130] Similar shifts and invasions have been documented in Long Island Sound and Narragansett Bay in the Atlantic.[131]
19. ***Global marine mammal diversity is projected to decline at lower latitudes and increase at higher latitudes due to changes in temperatures and sea ice, with complete loss of optimal habitat for as many as 11 species by mid-century; seal populations living in tropical and temperate waters are particularly at risk to future declines.***[132]
20. Higher nighttime temperatures and cumulative seasonal rainfalls were correlated with changes in the arrival times of amphibians to wetland breeding sites in South Carolina over a 30-year time period (1978-2008).[133]
21. Seedling survival of nearly 20 resident and migrant tree species decreased during years of lower rainfall in the Southern Appalachians and the Piedmont areas, indicating that reductions in native species and limited replacement by invading species were likely under climate change.[134]
22. Widespread declines in body size of resident and migrant birds at a bird-banding station in western Pennsylvania were documented over a 40-year period; body sizes of breeding adults were negatively correlated with mean regional temperatures from the preceding year.[85]
23. Over the last 130 years (1880-2010), native bees have advanced their spring arrival in the northeastern U.S. by an average of 10 days, primarily due to increased warming. Plants have also showed a trend of earlier blooming, thus helping preserve the synchrony in timing between plants and pollinators.[135]
24. In the Northwest Atlantic, 24 out of 36 commercially exploited fish stocks showed significant range (latitudinal and depth) shifts between 1968 and 2007 in response to increased sea surface and bottom temperatures.[55]
25. Increases in maximum, and decreases in the annual variability of, sea surface temperatures in the North Atlantic Ocean have promoted growth of small phytoplankton and led to a reorganization in the species composition of primary (phytoplankton) and secondary (zooplankton) producers.[136]
26. Changes in female polar bear reproductive success (decreased litter mass and numbers of yearlings) along the north Alaska coast have been linked to changes in body size and/or body condition following years with lower availability of optimal sea ice habitat.[137]
27. Water temperature data and observations of migration behaviors over a 34-year time period showed that adult pink salmon migrated earlier into Alaskan creeks, and fry advanced the timing of migration out to sea. Shifts in migration timing may increase the potential for a mismatch in optimal environmental conditions for early life stages, and continued warming trends will likely increase pre-spawning mortality and egg mortality rates.[87]
28. Warmer springs in Alaska have caused earlier onset of plant emergence, and decreased spatial variation in growth and availability of forage to breeding caribou. This ultimately reduced calving success in caribou populations.[138]
29. ***Many Hawaiian mountain vegetation types were found to vary in their sensitivity to changes in moisture availability; consequently, climate change will likely influence elevation-related vegetation patterns in this region.***[139]
30. ***Sea level is predicted to rise by 1.6 to 3.3 feet in Hawaiian waters by 2100, consistent with global projections of 1 to 4 feet of sea level rise (see Ch. 2: Our Changing Climate, Key Message 10). This is projected to increase wave heights, the duration of turbidity, and the amount of re-suspended sediment in the water; consequently, this will create potentially stressful conditions for coral reef communities.***[140]


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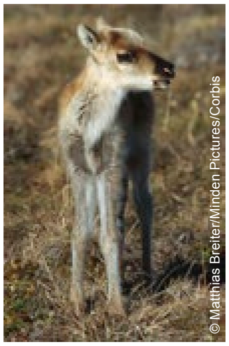
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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages and supporting chapter text summarize extensive evidence documented in the Ecosystems Technical Input Report, *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment*.[4] This foundational report evolved from a technical workshop held at the Gordon and Betty Moore Foundation in Palo Alto, CA, in January 2012 and attended by approximately 65 scientists. Technical inputs (127) on a wide range of topics related to ecosystems were also received and reviewed as part of the Federal Register Notice solicitation for public input.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

Description of evidence base

The author team digested the contents of more than 125 technical input reports on a wide array of topics to arrive at this key message. The foundational Technical Input Report[4] was the primary source used.

Studies have shown that increasing precipitation is already resulting in declining water quality in many regions of the country, particularly by increasing nitrogen loading.[10,11,12,13,14] This is because the increases in flow can pick up and carry greater loads of nutrients like nitrogen to rivers.[11,12,13,14]

One model for the Mississippi River Basin, based on a doubling of CO_2, projects that increasing discharge and nitrogen loading will lead to larger algal blooms in the Gulf of Mexico and a larger dead zone.[28] The Gulf of Mexico is the recipient system for the Mississippi Basin, receiving all of the nitrogen that is carried downriver but not removed by river processes, wetlands, or other ecosystems.

Several models project that declining streamflow, due to the combined effects of climate change and water withdrawals, will cause local extinctions of fish and other aquatic organisms,[7] particularly trout in the interior western U.S. (composite of 10 models, A1B scenario).[8] The trout study[8] is one of the few studies of impacts on fish that uses an emissions scenario and a combination of climate models. The researchers studied four different trout species. Although there were variations among species, their overall conclusion was robust across species for the composite model.

Water quality can also be negatively affected by increasing temperatures. There is widespread evidence that warmer lakes can promote the growth of harmful algal blooms, which produce toxins.[31]

New information and remaining uncertainties

Recent research has improved understanding of the relative importance of the effects of climate and human actions (for example, fertilization) on nitrogen losses from watersheds,[10,12] and how the interactions between climate and human actions (for example, water withdrawals) will affect fish populations in the west.[7,8] However, few studies have projected the impacts of future climate change on water quality. Given the tight link between river discharge and pollutants, only areas of the U.S. that are projected to see increases in precipitation will see increases in pollutant transport to rivers. It is also important to note that pollutant loading – for example, nitrogen fertilizer use – is often more important as a driver of water pollution than climate.[10,12]

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **high** confidence that climate change impacts on ecosystems reduce their ability to improve water quality and regulate water flows.

It is well established that precipitation and associated river discharge are major drivers of water pollution in the form of excess nutrients, sediment, and dissolved organic carbon (DOC) transport into rivers. Increases in precipitation in many regions of the country are therefore contributing to declines in water quality in those areas. However, those areas of the country that will see reduced precipitation may experience water-quality improvement; thus, any lack of agreement on future water-quality impacts of climate change may be due to locational differences.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms.

Description of evidence base

The author team digested the contents of more than 125 technical input reports on a wide array of topics to arrive at this key message. The foundational Technical Input Report[4] was the primary source used.

Fires: Climate change has increased the potential for extremely large fires with novel social, economic, and environmental impacts. In 2011, more than 8 million acres burned, with significant human mortality and property damage ($1.9 billion).[38] Warming and decreased precipitation have made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic, and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss.

Floods: Natural ecosystems such as salt marshes, reefs, mangrove forests, and barrier islands defend coastal ecosystems and infrastructure against flooding due to storm surges. The loss of these natural features due to coastal development, erosion, and sea level rise render coastal ecosystems and infrastructure more vulnerable to catastrophic damage during or after extreme events (see Ch. 25: Coasts).[36] Floodplain wetlands, which are also vulnerable to loss by inundation, absorb floodwaters and reduce the impact of high flows on river-margin lands. In the Northeast, a sea level rise of 1.6 feet (within the range of 1 to 4 feet projected for 2100; Ch. 2: Our Changing Climate, Key Message 9) will dramatically increase impacts of storm surge on people (47% increase) and property loss (73% increase) in Long Island.[37]

Storms: Natural ecosystems have a capacity to buffer extreme weather events that produce sudden increases in water flow and materials. These events reduce the amount of time water is in contact with sites that support the plants and microbes that remove pollutants (Chapter 25: Coasts).[36]

New information and remaining uncertainties

A new analytical framework was recently developed to generate insights into the interactions among the initial state of ecosystems, the type and magnitude of disturbance, and effects of disturbance.[34] Progress in understanding these relationships is critical for predicting how human activities and climate change, including extreme events like droughts, floods, and storms, will interact to affect ecosystems.

Uncertainties: The ability of ecosystems to buffer extreme events is extremely difficult to assess and quantify, as it requires understanding of complex ecosystem responses to very rare events. However, it is clear that the loss of this buffering ecosystem service is having important effects on coastal and fire-prone ecosystems across the United States.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **high** confidence that climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like droughts, floods, and storms.

Ecosystem responses to climate change will vary regionally. For example, whether salt marshes and mangroves will be able to accrue sediment at rates sufficient to keep ahead of sea level rise and maintain their protective function will vary by region.

Climate has been the dominant factor controlling burned area during the 20th century, even during periods of fire suppression by forest management,[40,111] and the area burned annually has increased steadily over the last 20 years concurrent with warming and/or drying climate. Warming and decreased precipitation have also made fire-prone ecosystems more vulnerable to "mega-fires" – large fires that are unprecedented in their social, economic, and environmental impacts. Large fires put people living in the urban-wildland interface at risk for health problems and property loss. In 2011 alone, 8.3 million acres burned in wildfires, causing 15 deaths and property losses greater than $1.9 billion.[38]

KEY MESSAGE #3 TRACEABLE ACCOUNT

Landscapes and seascapes are changing rapidly, and species, including many iconic species, may disappear from regions where they have been prevalent or become extinct, altering some regions so much that their mix of plant and animal life will become almost unrecognizable.

Description of evidence base

The analysis for the Technical Input Report applied a range of future climate scenarios and projected biome changes across 5% to about 20% of the land area in the U.S. by 2100.[4] Other analyses support these projections.[39] Studies predict that wildfire will be a major driver of change in some areas, including Yellowstone National Park[40] and the Arctic.[41] These biome shifts will be associated with changes in species distributions.[43]

Evidence indicates that the most obvious changes will occur at the boundaries between ecosystems.[47,48,49,51] Plants and animals are already moving to higher elevations and latitudes in response to climate change,[43] with models projecting greater range shifts[8,46] and local extinctions in the future, leading to new plant and animal communities that may be unrecognizable in some regions.[4,45,46] One study on fish[8] used global climate models (GCMs) simulating conditions in the 2040s and 2080s under the A1B emissions scenario, with the choice of models reflecting predictions of high and low climate warming as well as an ensemble of ten models. Their models additionally accounted for biotic interactions. In a second study, a 30-year baseline (1971-2000) and output from two GCMs under the A2 scenario (continued increases in global emissions) were used to develop climate variables that effectively predict present and future species ranges.[46] Empirical data from the Sonoran Desert (n=39 plots) were used to evaluate species responses to past climate variability.

Iconic species: Wildfire is expected to damage and kill iconic desert species, including saguaro cactus.[63] Bark beetle outbreaks, which have been exacerbated by climate change, are damaging extensive areas of temperate and boreal conifer forests that are characteristic of the western United States.[64]

New information and remaining uncertainties

In addition to the Technical Input Report, more than 20 new studies of observed and predicted effects of climate change on biomes and species distribution were incorporated in the assessment.

While changes in ecosystem structure and biodiversity, including the distribution of iconic species, are occurring and are highly likely to continue, the impact of these changes on ecosystem services is unclear, that is, there is uncertainty about the impact that loss of familiar landscapes will have on people.

Assessment of confidence based on evidence

Based on the evidence base and uncertainties, confidence is **high** that familiar landscapes are changing so rapidly that iconic species may disappear from regions where they have been prevalent, altering some regions so much that their mix of plant and animal life will become almost unrecognizable. Many changes in species distribution have already occurred and will inevitably continue, resulting in the loss of familiar landscapes and the production of novel species assemblages.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Ecosystems Technical Input, *Phenology as a bio-indicator of climate change impacts on people and ecosystems: Towards an integrated national assessment approach*.[71] An additional 127 input reports, on a wide range of topics related to ecosystems, were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Many studies have documented an advance in springtime phenological events of species in response to climate warming. For example, long-term observations of lilac flowering indicate that the onset of spring has advanced one day earlier per decade across the northern hemisphere in response to increased winter and spring temperatures, and by 1.5 days per decade earlier in the western United States.[72,73] Other multi-decadal studies for plant species have documented similar trends for early flowering.[74,75] Evidence suggests that insect emergence from overwintering may become out of sync with pollen sources,[77] and that the beginning of bird and fish migrations are shifting.[82,83,84,85,86,87]

New information and remaining uncertainties

In addition to the Ecosystems Technical Input[71] many new studies have been conducted since the previous National Climate Assessment,[141] contributing to our understanding of the impacts of climate change on phenological events. Many studies, in many areas, have shown significant changes in phenology, including spring bud burst, emergence from overwintering, and migration shifts.

A key uncertainty is "phase effects" where organisms are so out of phase with their natural phenology that outbreaks of pests occur, species emerge and cannot find food, or pollination is disrupted. This will vary with specific species and is therefore very difficult to predict.[70]

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is very high confidence that the timing of critical events, such as spring bud burst, emergence from overwintering, and the start of migrations, has shifted, leading to important impacts on species and habitats.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Whole system management is often more effective than focusing on one species at a time, and can help reduce the harm to wildlife, natural assets, and human well-being that climate disruption might cause.

Description of evidence base

Adaptation planning for conservation at federal[92,93,94] and state levels,[95] is focused on cooperation between scientists and managers.[34,94,96,97] Development of ecosystem-based whole system management[98] utilizes concepts about "biodiversity and ecosystem services to help people adapt to climate change."[99] An example is the use of coastal wetlands or mangroves rather than built infrastructure like seawalls or levees to protect coastal regions from storms (Chapter 25: Coasts).[100]

New information and remaining uncertainties

Adaptation strategies to protect biodiversity include: 1) habitat manipulations, 2) conserving populations with higher genetic diversity or more plastic behaviors or morphologies, 3) changing seed sources for re-planting to introduce species or ecotypes that are better suited for future climates, 4) managed relocation (sometimes referred to as assisted migration) to help move species and populations from current locations to those areas expected to become more suitable in the future, and 5) ex-situ conservation such as seed banking and captive breeding.[92,94,96,97,102] Alternative approaches focus on identifying and protecting features that are important for biodiversity and are projected to be less altered by climate change. The idea is to conserve the physical conditions that contribute to high levels of biodiversity so that species and populations can find suitable areas in the future.[104]

Assessment of confidence based on evidence

Given the evidence and remaining uncertainties, there is **very high** confidence that ecosystem-based management approaches are increasingly prevalent, and provide options for reducing the harm to biodiversity, ecosystems, and the services they provide to society. The effectiveness of these actions is much less certain, however.

Climate Change Impacts in the United States

CHAPTER 9
HUMAN HEALTH

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

9 HUMAN HEALTH

Key Messages

1. **Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and disease-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States.**
2. **Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.**
3. **Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.**
4. **Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.**

Climate change, together with other natural and human-made health stressors, influences human health and disease in numerous ways. Some existing health threats will intensify and new health threats will emerge. Not everyone is equally at risk. Important considerations include age, economic resources, and location. Preventive and adaptive actions, such as setting up extreme weather early warning systems and improving water infrastructure, can reduce the severity of these impacts, but there are limits to the effectiveness of such actions in the face of some projected climate change threats.

Climate change presents a global public health problem, with serious health impacts predicted to manifest in varying ways in different parts of the world. Public health in the U.S. can be affected by disruptions of physical, biological, and ecological systems, including disturbances originating in the U.S. and elsewhere. Health effects of these disruptions include increased respiratory and cardiovascular disease, injuries and premature deaths related to extreme weather events, changes in the prevalence and geographical distribution of food- and waterborne illnesses and other infectious diseases, and threats to mental health.

Key weather and climate drivers of health impacts include increasingly frequent, intense, and longer-lasting extreme heat, which worsens drought, wildfire, and air pollution risks; increasingly frequent extreme precipitation, intense storms, and changes in precipitation patterns that lead to drought and ecosystem changes (Ch. 2: Our Changing Climate); and rising sea levels that intensify coastal flooding and storm surge (Ch. 25: Coasts). Key drivers of vulnerability include the attributes of certain groups (age, socioeconomic status, race, current level of health – see Ch. 12: Indigenous Peoples for examples of health impacts on vulnerable populations) and of place (floodplains, coastal zones, and urban areas), as well as the resilience of critical public health infrastructure. Multi-stressor situations, such as impacts on vulnerable populations following natural disasters that also damage the social and physical infrastructure necessary for resilience and emergency response, are particularly important to consider when preparing for the impacts of climate change on human health.

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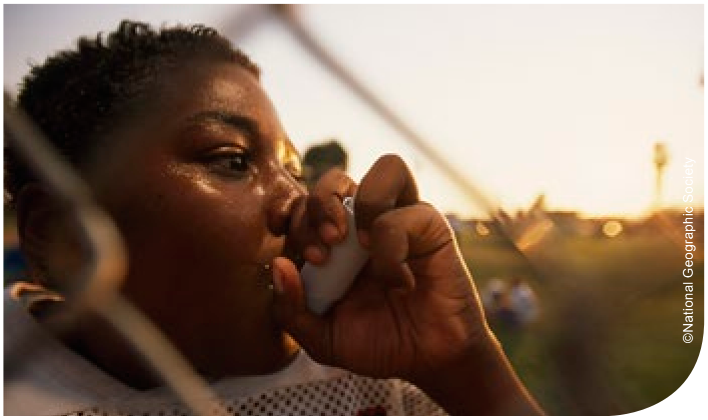
Key Message 1: Wide-ranging Health Impacts

Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and disease-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States.

Air Pollution



Climate change is projected to harm human health by increasing ground-level ozone and/or particulate matter air pollution in some locations. Ground-level ozone (a key component of smog) is associated with many health problems, such as diminished lung function, increased hospital admissions and emergency room visits for asthma, and increases in premature deaths.[1,2,3] Factors that affect ozone formation include heat, concentrations of precursor chemicals, and methane emissions, while particulate matter concentrations are affected by wildfire emissions and air stagnation episodes, among other factors.[4,5] By increasing these different factors, climate change is projected to lead to increased concentration of ozone and particulate matter in some regions.[6,7,8,9] Increases in global temperatures could cause associated increases in premature deaths related to worsened ozone and particle pollution. Estimates made assuming no change in regulatory controls or population characteristics have ranged from 1,000 to 4,300 additional premature deaths nationally per year by 2050 from combined ozone and particle health effects.[10,11] There is less certainty in the responses of airborne particles to climate change than there is about the response of ozone. Health-related costs of the current effects of ozone air pollution exceeding national standards have been estimated at $6.5 billion (in 2008 U.S. dollars) nationwide, based on a U.S. assessment of health impacts from ozone levels during 2000 to 2002.[12,13]

Climate Change Projected to Worsen Asthma

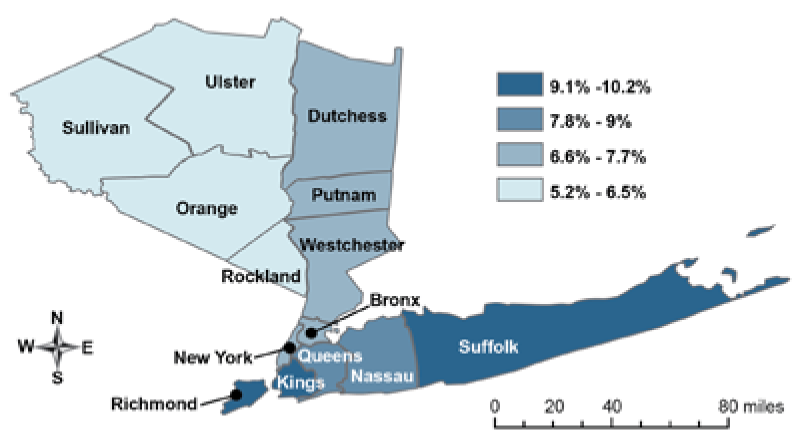


Figure 9.1. Projected increases in temperature, changes in wind patterns, and ecosystem changes will all affect future ground-level ozone concentrations. Climate projections using an increasing emissions scenario (A2) suggest that ozone concentrations in the New York metropolitan region will increase because of future climate change. This figure shows the estimated increase in ozone-related emergency room visits for children in New York in the 2020s (compared to the mid-1990s) resulting from climate change related increases in ozone concentrations. The results from this modeling exercise are shown as a percent change in visits specifically attributed to ozone exposure. For example, the 10.2% increase in Suffolk County represents five additional emergency room visits that could be attributed to increased ozone exposure over the baseline of 46 ozone-related visits from the mid-1990s. In 2010, an estimated 25.7 million Americans had asthma, which has become a problem in every state. (Figure source: Sheffield et al. 2011[14]).

Allergens

Climate change, resulting in more frost-free days and warmer seasonal air temperatures, can contribute to shifts in flowering time and pollen initiation from allergenic plant species, and increased CO_2 by itself can elevate production of plant-based allergens.[14,15,16,17,18,19] Higher pollen concentrations and longer pollen seasons can increase allergic sensitizations and asthma episodes,[20,21,22] and diminish productive work and school days.[19,22,23] Simultaneous exposure to toxic air pollutants can worsen allergic responses.[24,25,26] Extreme rainfall and rising temperatures can also foster indoor air quality problems, including the growth of indoor fungi and molds, with increases in respiratory and asthma-related conditions.[27] Asthma prevalence (the percentage of people who have ever been diagnosed with asthma and still have asthma) increased nationwide from 7.3% in 2001 to 8.4% in 2010. Asthma visits in primary care settings, emergency room visits, and hospitalizations were all stable from 2001 to 2009, and asthma death rates per 1,000 persons with asthma declined from 2001 to 2009.[28] To the extent that increased pollen exposures occur, patients and their physicians will face increased challenges in maintaining adequate asthma control.

Ragweed Pollen Season Lengthens

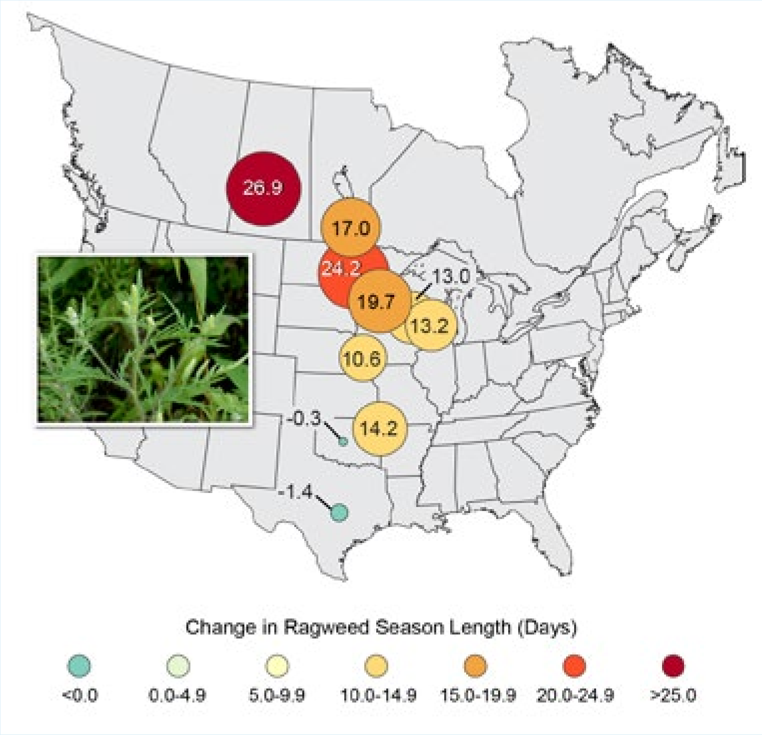


Figure 9.2. Ragweed pollen season length has increased in central North America between 1995 and 2011 by as much as 11 to 27 days in parts of the U.S. and Canada in response to rising temperatures. Increases in the length of this allergenic pollen season are correlated with increases in the number of days before the first frost. As shown in the figure, the largest increases have been observed in northern cities. (Data updated from Ziska et al. 2011[19]; Photo credit: Lewis Ziska, USDA).

Wildfires

Climate change is currently increasing the vulnerability of many forests to wildfire. Climate change is projected to increase the frequency of wildfire in certain regions of the United States (Ch. 7: Forests).[17,29] Long periods of record high temperatures are associated with droughts that contribute to dry conditions and drive wildfires in some areas.[30] Wildfire smoke contains particulate matter, carbon monoxide, nitrogen oxides, and various volatile organic compounds (which are ozone precursors)[31] and can significantly reduce air quality, both locally and in areas downwind of fires.[32,33] Smoke exposure increases respiratory and cardiovascular hospitalizations, emergency department visits, and medication dispensations for asthma, bronchitis, chest pain, chronic obstructive pulmonary disease (commonly known by its acronym, COPD), respiratory infections, and medical visits for lung illnesses.[32,34,35] It has been associated with hundreds of thousands of deaths annually, in an assessment of the global health risks from landscape fire smoke.[32,34,36,37] Future climate change is projected to increase wildfire risks and associated emissions, with harmful impacts on health.[17,38,39,40]

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Wildfire Smoke has Widespread Health Effects

Figure 9.3. Wildfires, which are projected to increase in some regions due to climate change, have health impacts that can extend hundreds of miles. Shown here, forest fires in Quebec, Canada, during July 2002 (red circles) resulted in up to a 30-fold increase in airborne fine particle concentrations in Baltimore, Maryland, a city nearly a thousand miles downwind. These fine particles, which are extremely harmful to human health, not only affect outdoor air quality, but also penetrate indoors, increasing the long-distance effects of fires on health.[41] An average of 6.4 million acres burned in U.S. wildfires each year between 2000 and 2010, with 9.5 and 9.1 million acres burned in 2006 and 2012, respectively.[42] Total global deaths from the effects of landscape fire smoke have been estimated at 260,000 to 600,000 annually between the years 1997 and 2006.[37] (Figure source: Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra satellite, Land Rapid Response Team, NASA/GSFC).

Temperature Extremes

Extreme heat events have long threatened public health in the United States.[43,44,45] Many cities, including St. Louis, Philadelphia, Chicago, and Cincinnati, have suffered dramatic increases in death rates during heat waves. Deaths result from heat stroke and related conditions,[44,45,46] but also from cardiovascular disease, respiratory disease, and cerebrovascular disease.[47,48] Heat waves are also associated with increased hospital admissions for cardiovascular, kidney, and respiratory disorders.[48,49,50] Extreme summer heat is increasing in the United States (Ch. 2: Our Changing Climate, Key Message 7),[51] and climate projections indicate that extreme heat events will be more frequent and intense in coming decades (Ch. 2: Our Changing Climate, Key Message 7).[2,52,53,54]

Some of the risks of heat-related sickness and death have diminished in recent decades, possibly due to better forecasting, heat-health early warning systems, and/or increased access to air conditioning for the U.S. population.[55] However, extreme heat events remain a cause of preventable death nationwide. Urban heat islands, combined with an aging population and increased urbanization, are projected to increase the vulnerability of urban populations to heat-related health impacts in the future (Ch. 11: Urban).[56,57,58]

Milder winters resulting from a warming climate can reduce illness, injuries, and deaths associated with cold and snow. Vulnerability to winter weather depends on many non-climate factors, including housing, age, and baseline health.[59] While deaths and injuries related to extreme cold events are projected to decline due to climate change, these reductions are not expected to compensate for the increase in heat-related deaths.[60,61]

Projected Temperature Change of Hottest Days

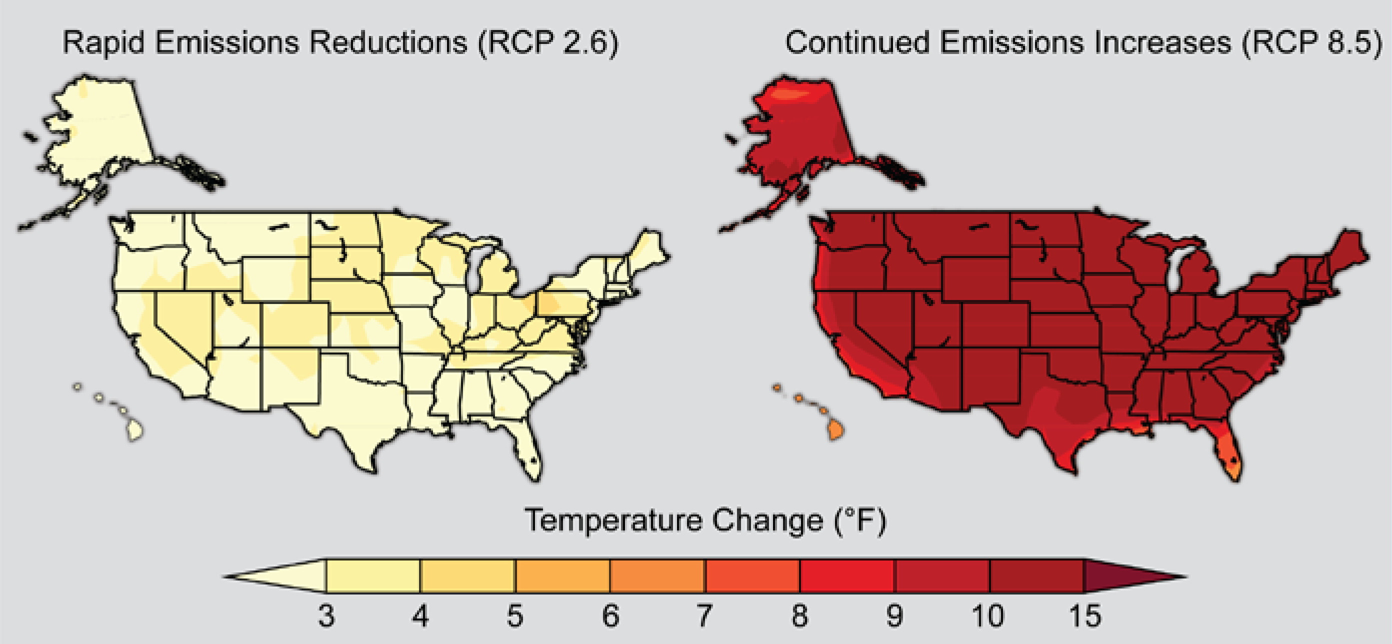

Figure 9.4. The maps show projected increases in the average temperature on the hottest days by late this century (2081-2100) relative to 1986-2005 under a scenario that assumes a rapid reduction in heat-trapping gases (RCP 2.6) and a scenario that assumes continued increases in these gases (RCP 8.5). The hottest days are those so hot they occur only once in 20 years. Across most of the continental United States, those days will be about 10ºF to 15ºF hotter in the future under the higher emissions scenario. (Figure source: NOAA NCDC / CICS-NC).

Precipitation Extremes: Heavy Rainfall, Flooding, and Droughts

The frequency of heavy precipitation events has already increased for the nation as a whole, and is projected to increase in all U.S. regions (Ch. 2: Our Changing Climate).[54,62] Increases in both extreme precipitation and total precipitation have contributed to increases in severe flooding events in certain regions (see Ch. 2: Our Changing Climate, Figure 2.21). Floods are the second deadliest of all weather-related hazards in the United States, accounting for approximately 98 deaths per year,[63] most due to drowning.[64] Flash floods (see Ch. 3: Water, "Flood Factors and Flood Types") and flooding associated with tropical storms result in the highest number of deaths.[63]

In addition to the immediate health hazards associated with extreme precipitation events when flooding occurs, other hazards can often appear once a storm event has passed. Elevated waterborne disease outbreaks have been reported in the weeks following heavy rainfall,[65] although other variables may affect these associations.[66] Water intrusion into buildings can result in mold contamination that manifests later, leading to indoor air quality problems. Buildings damaged during hurricanes are especially susceptible to water intrusion. Populations living in damp indoor environments experience increased prevalence of asthma and other upper respiratory tract symptoms, such as coughing and wheezing[67] as well as lower respiratory tract infections such as pneumonia, Respiratory Syncytial Virus (RSV), and RSV pneumonia (see Figure 9.7).[68]

At the opposite end of precipitation extremes, drought also poses risks to public health and safety.[69] Drought conditions may increase the environmental exposure to a broad set of health hazards including wildfires, dust storms, extreme heat events, flash flooding, degraded water quality, and reduced water quantity. Dust storms associated with drought conditions contribute to degraded air quality due to particulates and have been associated with increased incidence of Coccidioidomycosis (Valley fever), a fungal pathogen, in Arizona and California.[70]

Disease Carried by Vectors

Climate is one of the factors that influence the distribution of diseases borne by vectors (such as fleas, ticks, and mosquitoes, which spread pathogens that cause illness).[71,72,73,74,75,76,77,78] The geographic and seasonal distribution of vector populations, and the diseases they can carry, depend not only on climate but also on land use, socioeconomic and cultural factors, pest control, access to health care, and human responses to disease risk, among other factors.[72,73,79,80,81] Daily, seasonal, or year-to-year climate variability can sometimes result in vector/pathogen adaptation and shifts or expansions in their geographic ranges.[73,74,81] Such shifts can alter disease incidence depending on vector-host interaction, host immunity, and pathogen evolution.[71] North Americans are currently at risk from numerous vector-borne diseases, including Lyme,[75,82,83,84] dengue fever,[85] West Nile virus,[86] Rocky Mountain spotted fever,[87] plague, and tularemia.[88] Vector-borne pathogens not currently found in the United States, such as chikungunya, Chagas disease, and Rift Valley fever viruses, are also threats. Climate change effects on the geographical distribution and incidence of vector-borne diseases in other countries where these diseases are already found can also affect North Americans, especially as a result of increasing trade with, and travel to, tropical and subtropical areas.[74,81] Whether climate change in the U.S. will increase the chances of domestically acquiring diseases such as dengue fever is uncertain, due to vector-control efforts and lifestyle factors, such as time spent indoors, that reduce human-insect contact.

Infectious disease transmission is sensitive to local, small-scale differences in weather, human modification of the landscape, the diversity of animal hosts,[83] and human behavior that affects vector-human contact, among other factors. There is a need for finer-scale, long-term studies to help quantify the relationships among weather variables, vector range, and vector-borne pathogen occurrence, the consequences of shifting distributions of vectors and pathogens, and the impacts on human behavior. Enhanced vector surveillance and human disease tracking are needed to address these concerns.


James Gathany, CDC

The *Culex tarsalis* mosquito is a vector that transmits West Nile Virus.

TRANSMISSION CYCLE OF LYME DISEASE

The development and survival of blacklegged ticks, their animal hosts, and the Lyme disease bacterium, *Borrelia burgdorferi*, are strongly influenced by climatic factors, especially temperature, precipitation, and humidity. Potential impacts of climate change on the transmission of Lyme disease include: 1) changes in the geographic distribution of the disease due to the increase in favorable habitat for ticks to survive off their hosts;[89] 2) a lengthened transmission season due to earlier onset of higher temperatures in the spring and later onset of cold and frost; 3) higher tick densities leading to greater risk in areas where the disease is currently observed, due to milder winters and potentially larger rodent host populations; and 4) changes in human behaviors, including increased time outdoors, which may increase the risk of exposure to infected ticks.

Projected Changes in Tick Habitat

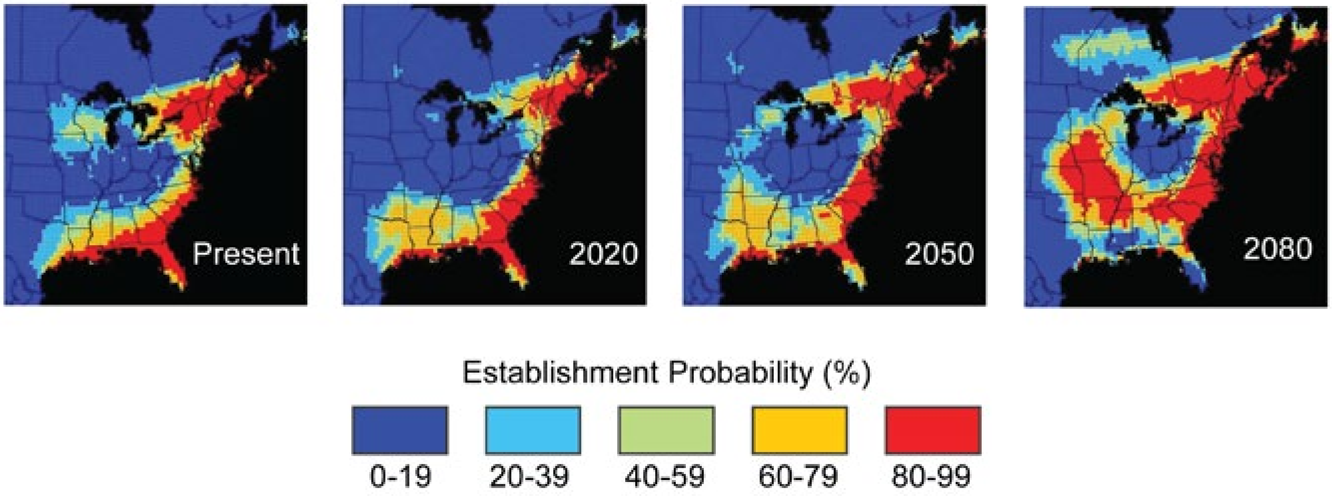

Figure 9.5. The maps show the current and projected probability of establishment of tick populations (*Ixodes scapularis*) that transmit Lyme disease. Projections are shown for 2020, 2050, and 2080. The projected expansion of tick habitat includes much of the eastern half of the country by 2080. For some areas around the Gulf Coast, the probability of tick population establishment is projected to decrease by 2080. (Figure source: adapted from Brownstein et al. 2005[90]).

Food- and Waterborne Diarrheal Disease

Diarrheal disease is a major public health issue in developing countries and, while not generally increasing in the United States, remains a persistent concern nonetheless. Exposure to a variety of pathogens in water and food causes diarrheal disease. Air and water temperatures, precipitation patterns, extreme rainfall events, and seasonal variations are all known to affect disease transmission.[65,91,92] In the United States, children and the elderly are most vulnerable to serious outcomes, and those exposed to inadequately or untreated groundwater will be among those most affected.

In general, diarrheal diseases including Salmonellosis and Campylobacteriosis are more common when temperatures are higher,[93,94] though patterns differ by place and pathogen. Diarrheal diseases have also been found to occur more frequently in conjunction with both unusually high and low precipitation.[95] Sporadic increases in streamflow rates, often preceded by rapid snowmelt[96] and changes in water treatment,[97] have also been shown to precede outbreaks. Risks of waterborne illness and beach closures resulting from changes in the magnitude of recent precipitation (within the past 24 hours) and in lake temperature are expected to increase in the Great Lakes region due to projected climate change.[98,99]

Projected Change in Heavy Precipitation Events

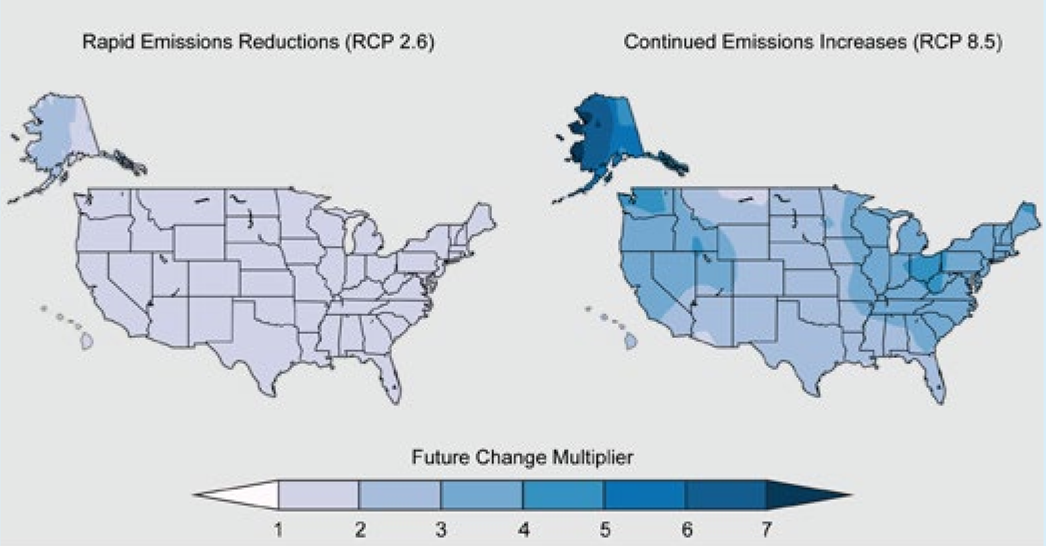

Figure 9.6. Maps show the increase in frequency of extreme daily precipitation events (a daily amount that now occurs just once in 20 years) by the later part of this century (2081-2100) compared to the latter part of the last century (1981-2000). Such extreme events are projected to occur more frequently everywhere in the United States. Under a rapid emissions reduction scenario (RCP 2.6), these events would occur nearly twice as often. For a scenario assuming continued increases in emissions (RCP 8.5), these events would occur up to five times as often. (Figure source: NOAA NCDC / CICS-NC).

Heavy Downpours are Increasing Exposure to Disease

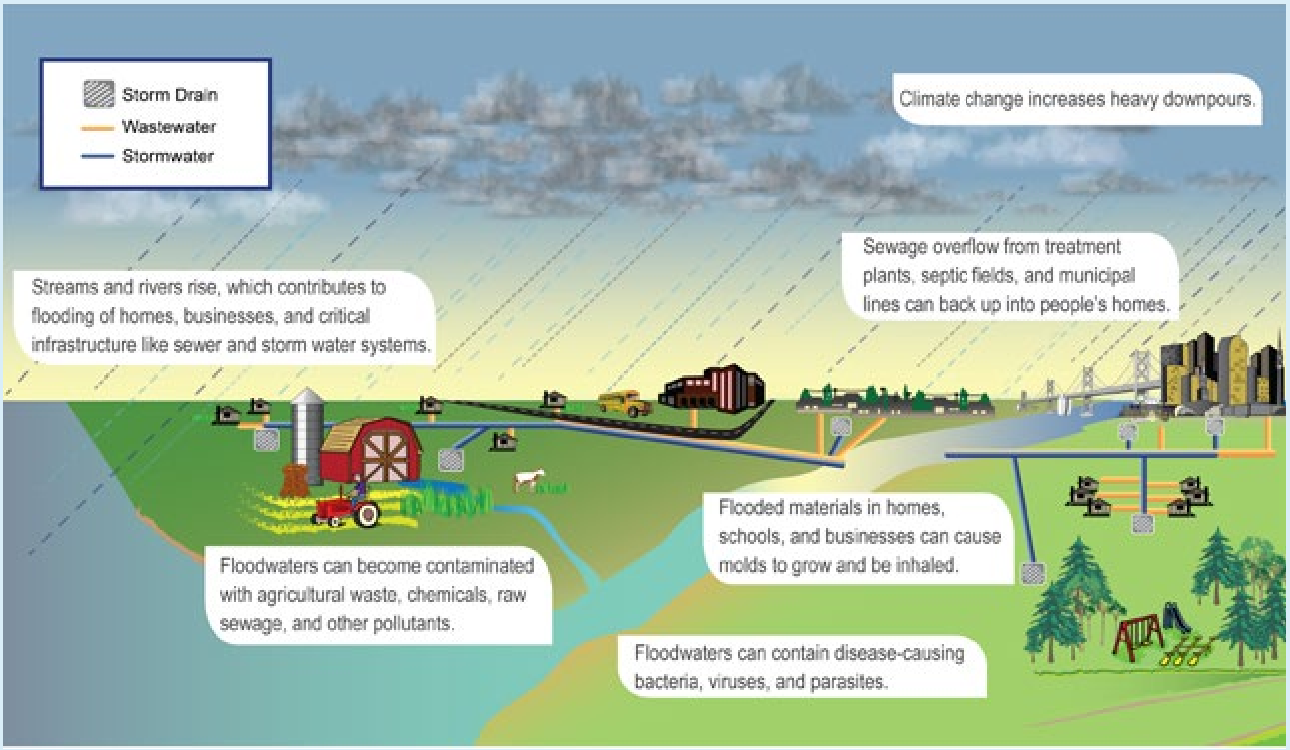

Figure 9.7. Heavy downpours, which are increasing in the United States, have contributed to increases in heavy flood events (Ch. 2: Our Changing Climate, Key Message 6). The figure above illustrates how people can become exposed to waterborne diseases. Human exposures to waterborne diseases can occur via drinking water, as well as recreational waters.[100,101,102,103] (Figure source: NOAA NCDC / CICS-NC).

Harmful Bloom of Algae

Figure 9.8. Remote sensing color image of harmful algal bloom in Lake Erie on October 9, 2011. The bright green areas have high concentrations of algae, which can be harmful to human health. The frequency and range of harmful blooms of algae are increasing.[102,103] Because algal blooms are closely related to climate factors, projected changes in climate could affect algal blooms and lead to increases in water- and food-borne exposures and subsequent cases of illness.[103] Other factors related to increases in harmful algal blooms include shifts in ocean conditions such as excess nutrient inputs.[101,102,103] (Figure source: NASA Earth Observatory[104]).

Food Security

Globally, climate change is expected to threaten food production and certain aspects of food quality, as well as food prices and distribution systems. Many crop yields are predicted to decline due to the combined effects of changes in rainfall, severe weather events, and increasing competition from weeds and pests on crop plants (Ch. 6: Agriculture, Key Message 6).[105,106] Livestock and fish production is also projected to decline.[107] Prices are expected to rise in response to declining food production and associated trends such as increasingly expensive petroleum (used for agricultural inputs such as pesticides and fertilizers).[108]

While the U.S. will be less affected than some other countries,[109,110] the nation will not be immune. Health can be affected in several ways. First, Americans with particular dietary patterns, such as Alaska Natives, will confront shortages of key foods (Ch. 12: Indigenous Peoples, Key Message 1).[111] Second, food insecurity increases with rising food prices.[112] In such situations, people cope by turning to nutrient-poor but calorie-rich foods, and/or they endure hunger, with consequences ranging from micronutrient malnutrition to obesity.[113] Third, the nutritional value of some foods is projected to decline. Elevated atmospheric CO_2 is associated with decreased plant nitrogen concentration, and therefore decreased protein, in many crops, such as barley, sorghum, and soy.[114] The nutrient content of crops is also projected to decline if soil nitrogen levels are suboptimal, with reduced levels of nutrients such as calcium, iron, zinc, vitamins, and sugars, although this effect is alleviated if sufficient nitrogen is supplied.[115] Fourth, farmers are expected to need to use more herbicides and pesticides because of increased growth of pests[116] and weeds[117] as well as decreased effectiveness[118] and duration[119] of some of these chemicals (Ch. 6: Agriculture). Farmers, farmworkers, and consumers will thus sustain increased exposure to these substances and their residues, which can be toxic. These climate change impacts on the nutritional value of food exist within a larger context in which other factors, such as agricultural practices, food distribution systems, and consumer food choices, also play key roles. Adaptation activities can reduce the health-related impacts of some of the anticipated food security challenges (Ch. 6: Agriculture).

Mental Health and Stress-related Disorders

Mental illness is one of the major causes of suffering in the United States, and extreme weather events can affect mental health in several ways.[120,121,122,123] First, following disasters, mental health problems increase, both among people with no history of mental illness, and those at risk – a phenomenon known as "common reactions to abnormal events." These reactions may be short-lived or, in some cases, long-lasting.[124] For example, research demonstrated high levels of anxiety and post-traumatic stress disorder among people affected by Hurricane Katrina,[125] and similar observations have followed floods[126] and heat waves.[127] Some evidence suggests wildfires have similar effects.[128] All of these events are increasingly fueled by climate change (see Ch. 2: Our Changing Climate). Other health consequences of intensely stressful exposures are also a concern, such as adverse birth outcomes including pre-term birth, low birth weight, and maternal complications.[129]

Second, some patients with mental illness are especially susceptible to heat.[130] Suicide rates vary with weather,[131] rising with high temperatures,[132] suggesting potential climate change impacts on depression and other mental illnesses. Dementia is a risk factor for hospitalization and death during heat waves.[127,133] Patients with severe mental illness such as schizophrenia are at risk during hot weather because their medications may interfere with temperature regulation or even directly cause hyperthermia.[134] Additional potential mental health impacts, less well understood, include the possible distress associated with environmental degradation[135] and displacement,[136] and the anxiety and despair that knowledge of climate change might elicit in some people (Ch. 12: Indigenous Peoples, Key Message 5).[122]

Key Message 2: Most Vulnerable at Most Risk

Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.

Climate change will increase the risk of climate-related illness and death for a number of vulnerable groups in the United States, as when Hurricane Katrina devastated New Orleans in 2005. Children, primarily because of physiological and developmental factors, will disproportionately suffer from the effects of heat waves,[47] air pollution, infectious illness, and trauma resulting from extreme weather events.[14,16,18,22,138,139,140,141] The country's older population also could be harmed more as the climate changes. Older people are at much higher risk of dying during extreme heat events.[45,47,139,142] Pre-existing health conditions also make older adults susceptible to cardiac and respiratory impacts of air pollution[26] and to more severe consequences from infectious diseases;[143] limited mobility among older adults can also increase flood-related health risks.[144] Limited resources and an already high burden of chronic health conditions, including heart disease, obesity, and diabetes, will place the poor at higher risk of health impacts from climate change than higher income groups.[26,47] Potential increases in food cost and limited availability of some foods will exacerbate current dietary inequalities and have significant health ramifications for the poorer segments of our population (Ch. 12: Indigenous Peoples, Key Message 1).[110,145]

Climate change will disproportionately affect low-income communities and some communities of color (Ch. 12: Indigenous Peoples, Key Message 2),[139,149,151,152,153,154,155,156,157] raising environmental justice concerns. Existing health disparities[153,158,159] and other inequities[160,161] increase vulnerability. Climate change related issues that have an equity component include heat waves, air quality, and extreme weather and climate events. For example, Hurricane Katrina demonstrated how vulnerable certain groups of people were to extreme weather events, because many low-income and of-color New Orleans residents were killed, injured, or had difficulty evacuating and recovering from the storm.[154,155,156,161,162,163,164]

Elements of Vulnerability to Climate Change

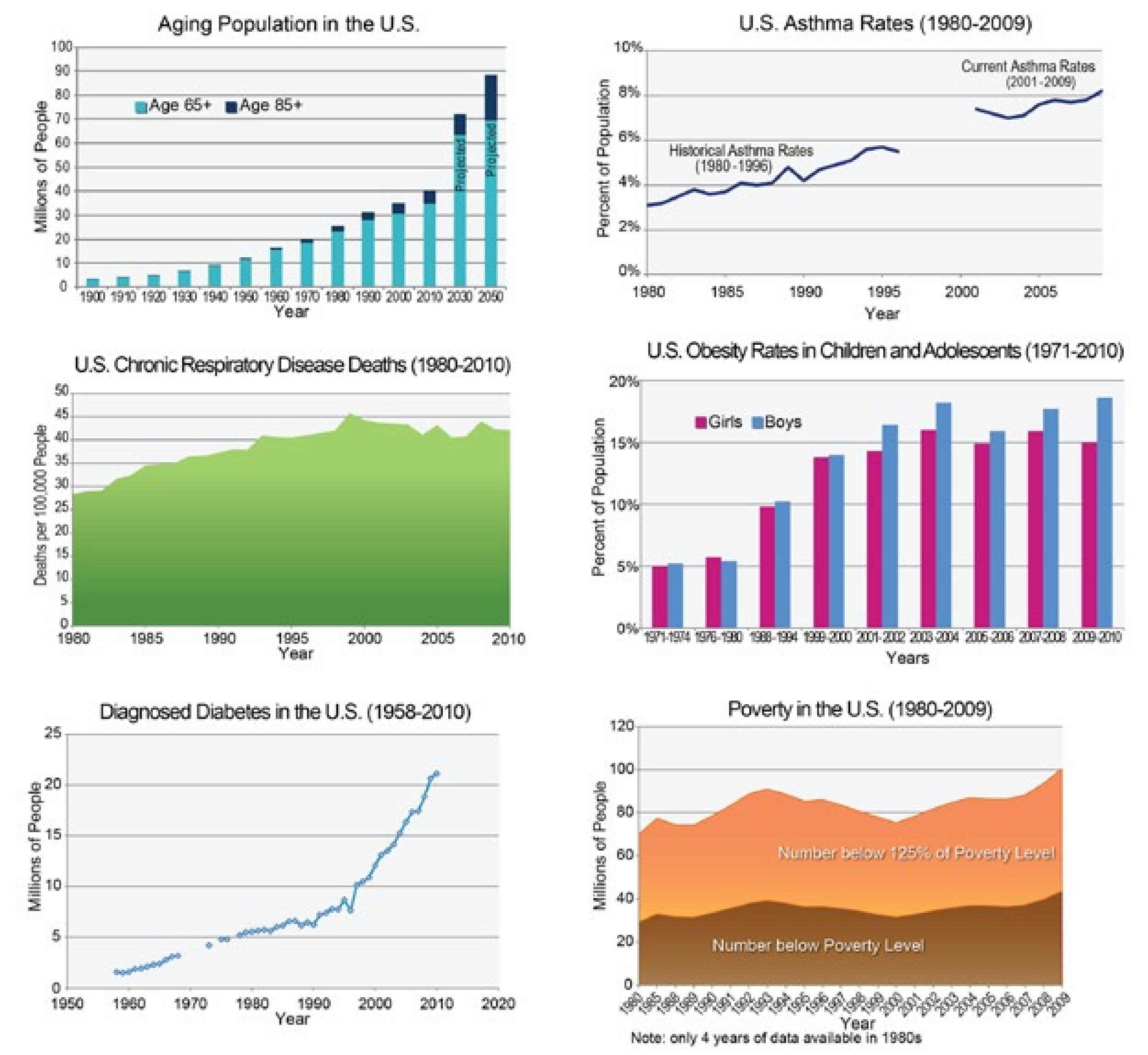

Figure 9.9. A variety of factors can increase the vulnerability of a specific demographic group to health effects due to climate change. For example, older adults are more vulnerable to heat stress because their bodies are less able to regulate their temperature. Overall population growth is projected to continue to at least 2050, with older adults comprising an increasing proportion of the population. Similarly, there are an increasing number of people who are obese and have diabetes, heart disease, or asthma, which makes them more vulnerable to a range of climate-related health impacts. Their numbers are also rising. The poor are less able to afford the kinds of measures that can protect them from and treat them for various health impacts. (Data from CDC; Health E-Stat; U.S. Census Bureau 2010, 2012; and Akinbami et al. 2011[137]).

SOCIETAL SYSTEM FAILURES DURING EXTREME EVENTS

We have already seen multiple system failures during an extreme weather event in the United States, as when Hurricane Katrina struck New Orleans.[146] Infrastructure and evacuation failures and collapse of critical response services during a storm is one example of multiple system failures. Another example is a loss of electrical power during a heat wave or wildfires, which can reduce food and water safety.[147] Air conditioning has helped reduce illness and death due to extreme heat,[148] but if power is lost, everyone is vulnerable. By their nature, such events can exceed our capacity to respond.[79] In succession, these events severely deplete our resources needed to respond, from the individual to the national scale, but disproportionately affect the most vulnerable populations.[149]

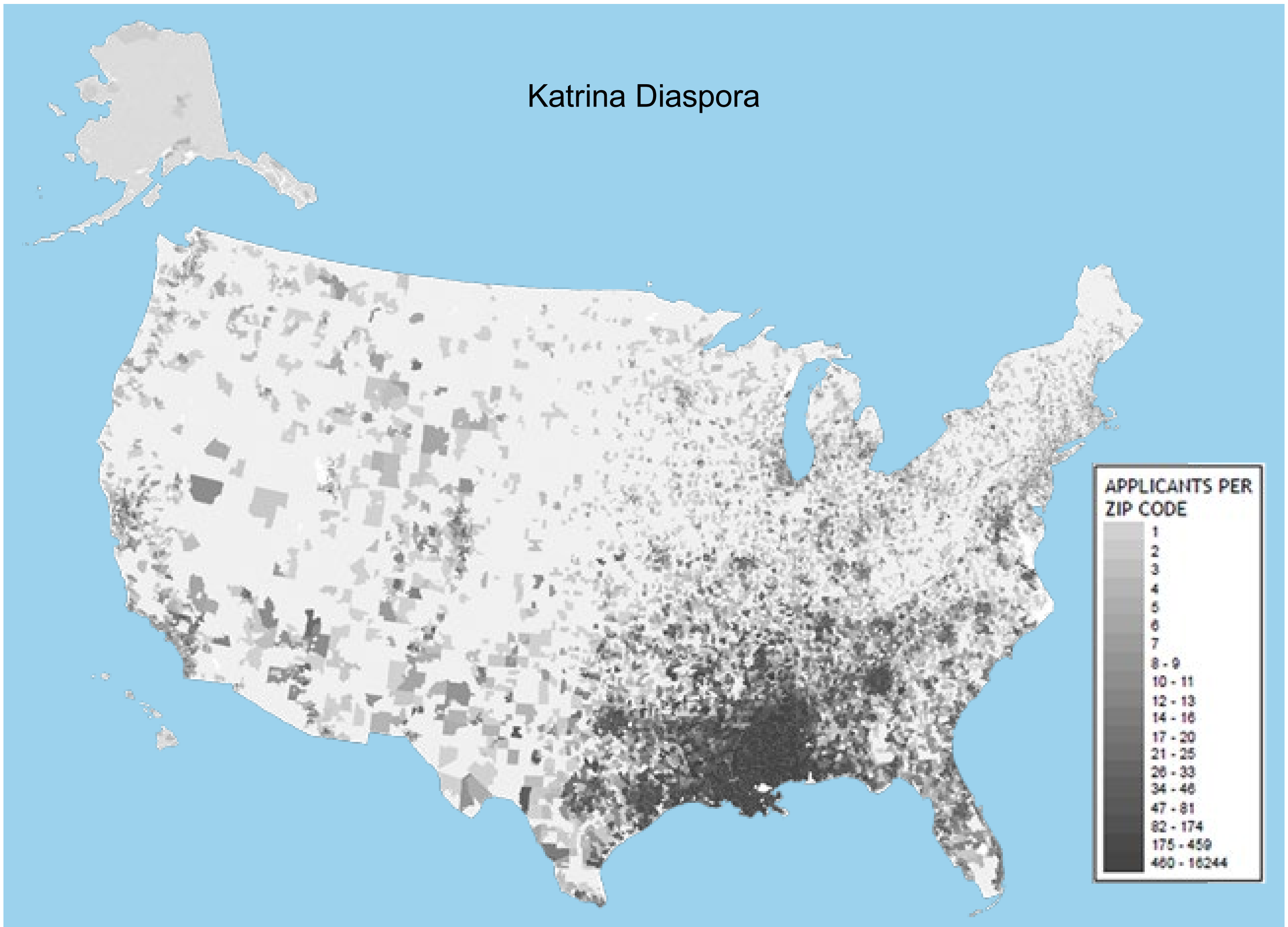

Figure 9.10. This map illustrates the national scope of the dispersion of displaced people from Hurricane Katrina. It shows the location by zip code of the 800,000 displaced Louisiana residents who requested federal emergency assistance. The evacuees ended up dispersed across the entire nation, illustrating the wide-ranging impacts that can flow from extreme weather events, such as those that are projected to increase in frequency and/or intensity as climate continues to change (Ch. 2: Our Changing Climate, Key Message 8). (Figure source: Kent 2006[150]).

MULTIPLE CLIMATE STRESSORS AND HEALTH

Climate change impacts add to the *cumulative* stresses currently faced by vulnerable populations including children, the elderly, the poor, some communities of color, and people with chronic illnesses. These populations, and others living in certain places such as cities, floodplains, and coastlines, are more vulnerable not only to extreme events but also to ongoing, persistent climate-related threats. These threats include poor air quality, heat, drought, flooding, and mental health stress. Over time, the accumulation of these stresses will be increasingly harmful to these populations.

Key Message 3: Prevention Provides Protection

Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.

Prevention is a central tenet of public health. Many conditions that are difficult and costly to treat when a patient gets to the doctor could be prevented before they occur at a fraction of the cost. Similarly, many of the larger health impacts associated with climate change can be prevented through early action at significantly lower cost than dealing with them after they occur.[153,165] Early preventive interventions, such as early warnings for extreme weather, can be particularly cost-effective.[166,167,168] As with many illnesses,[169] once impacts are apparent, even the best adaptive efforts can be overwhelmed, and damage control becomes the priority.[62]

Activities that reduce carbon pollution often also provide co-benefits in the form of preventive health measures. For example, reliance on cleaner energy sources for electricity production[174] and more efficient and active transport, like biking or walking,[175] can have immediate public health benefits, through improved air quality and lowered rates of obesity, diabetes, and heart disease.[176] Reducing carbon pollution also reduces long-term adverse climate-health impacts, thus producing cost savings in the near and longer term.[176] Preventing exposures to other climate-sensitive impacts already apparent can similarly result in cost savings. For instance, heat wave early warning systems protect vulnerable groups very effectively and are much less expensive than treating and coping with heat illnesses. Systems that monitor for early outbreaks of disease are also typically much less expensive than treating communities once outbreaks take hold.[12,49,177]

LARGE-SCALE ENVIRONMENTAL CHANGE FAVORS DISEASE EMERGENCE

Climate change is causing large-scale changes in the environment, increasing the likelihood of the emergence or reemergence of unfamiliar disease threats.[170] Factors include shifting ranges of disease-carrying pests, lack of immunity and preparedness, inadequate disease monitoring, and increasing global travel. Diseases including Lyme disease and dengue fever pose increasing health threats to the U.S. population; the number of U.S. patients hospitalized with dengue fever more than tripled from 2000 to 2007.[171] Although most cases of dengue fever during that time period were acquired outside the contiguous United States, the introduction of infected people into areas where the dengue virus vector is established increases the risk of locally acquired cases. The public health system is not fully prepared to monitor or respond to these growing disease risks. The introduction of new diseases into non-immune populations has been and continues to be a major challenge in public health. There are concerns that climate change may provide opportunities for pathogens to expand or shift their geographic ranges.[172,173]

Effective communication is a fundamental part of prevention. The public must understand risk in order to endorse proactive risk management. The public is familiar with the health risks of smoking, but not so for climate change. When asked about climate change impacts, Americans do not mention health impacts,[178] and when asked about health impacts specifically, most believe it will affect people in a different time or place.[179] But diverse groups of Americans find information on health impacts to be helpful once received, particularly information about the health benefits of mitigation (reducing carbon emissions) and adaptation.[180]

Determining which types of prevention to invest in (such as monitoring, early warning systems, and land-use changes that reduce the impact of heat and floods) depends on several factors, including health problems common to that particular area, vulnerable populations, the preventive health systems already in place, and the expected impacts of climate change.[181] Local capacity to adapt is very important; unfortunately the most vulnerable populations also frequently have limited resources for managing climate-health risks.

Overall, the capacity of the American public health and health care delivery systems faces many challenges.[182] The cost of dealing with current health problems is diverting resources from preventing them in the first place. This makes the U.S. population more vulnerable.[183,184] Without careful consideration of how to prevent future impacts, similar patterns could emerge regarding the health impacts from climate change. However, efforts to quantify and map vulnerability factors at the community level are underway.[151,164,185]

There are public health programs in some locations that address climate-sensitive health issues, and integrating such programs into the mainstream public health toolkit as adaptation needs increase would improve public health resilience to climate change.[79,186,187] Given that these programs have demonstrated efficacy against current threats that are expected to worsen with climate change, it is prudent to invest in creating the strongest climate-health preparedness programs possible.[153] One survey highlighted opportunities to address climate change preparedness activities and climate-health research[181] before needs become more widespread. *America's Climate Choices: Adapting to the Impacts of Climate Choices* (Table 3.5) provides examples of health adaptation options.[187]

Key Message 4: Responses Have Multiple Benefits

Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.

Policies and other strategies intended to reduce carbon pollution and mitigate climate change can often have independent influences on human health. For example, reducing CO_2 emissions through renewable electrical power generation can reduce air pollutants like particles and sulfur dioxide. Efforts to improve the resiliency of communities and human infrastructure to climate change impacts can also improve human health. There is a growing recognition that the magnitude of health "co-benefits," like reducing both pollution and cardiovascular disease, could be significant, both from a public health and an economic standpoint.[176,188,189] Some climate change resilience efforts will benefit health, but potential co-harms should be considered when implementing these strategies. For example, although there are numerous benefits to urban greening, such as reducing the urban heat island effect while simultaneously promoting an active healthy lifestyle,[159,190,191] the urban planting of certain allergenic pollen producing species[22] could increase human pollen exposure and allergic illness. Increased pollen exposure has been linked to increased emergency department visits related to asthma and wheezing[192] in addition to respiratory allergic illnesses such as allergic rhinitis or hay fever.[193] The selective use of low to moderate pollen-producing species can decrease pollen exposure.[194]

Much of the focus of health co-benefits has been on reducing health-harming air pollution.[6,174,175,195,196] One study projects that replacing 50% of short motor vehicle trips with bicycle use and the other 50% with other forms of transportation like walking or public transit would avoid nearly 1,300 deaths in 11 midwestern metropolitan areas and create up to $8 billion in health benefits annually for the upper Midwest region.[188] Such multiple-benefit actions can reduce heat-trapping gas emissions that lead to climate change, improve air quality by reducing vehicle pollutant emissions, and improve fitness and health through increased physical activity.[99,197,198,199,200]

Innovative urban design could create increased access to active transport.[99] The compact geographical area found in cities presents opportunities to reduce energy use and emissions of heat-trapping gases and other air pollutants through active transit, improved building construction, provision of services, and infrastructure creation, such as bike paths and sidewalks.[197,201] Urban planning strategies designed to reduce the urban heat island effect, such as green/cool roofs, increased green space, parkland and urban canopy, could reduce indoor temperatures, improve indoor air quality, and could produce additional societal co-benefits by promoting social interaction and prioritizing vulnerable urban populations.[191,197]

Patterns of change related to improving health can also have co-benefits in terms of reducing carbon pollution and mitigating climate change. Current U.S. dietary guidelines and many health professionals have recommended diets higher in fruits and vegetables and lower in red meat as a means of helping


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to reduce the risk of cardiovascular disease and some cancers.[199,202,203] These changes in food consumption, and related changes to food production, could have co-benefits in terms of reducing greenhouse gas emissions. While the greenhouse gas footprint of the production of other foods, compared to sources such as livestock, is highly dependent on a number of factors, production of livestock currently accounts for about 30% of the U.S. total emissions of methane.[199,203,204] This amount of methane can be reduced somewhat by recovery methods such as the use of biogas digesters, but future changes in dietary practices, including those motivated by considerations other than climate change mitigation, could also have an effect on the amount of methane emitted to the atmosphere.[205]

In addition to producing health co-benefits,[206] climate change prevention and preparedness measures could also yield positive equity impacts. For example, several studies have found that communities of color and poor communities experience disproportionately high exposures to air pollution.[207,208] Climate change mitigation policies that improve local air quality thus have the potential to strongly benefit health in these communities.

An area where adaptation policy could produce more equitable health outcomes is with respect to extreme weather events. As discussed earlier, Hurricane Katrina demonstrated that communities of color, poor communities, and certain other vulnerable populations (like new immigrant communities) are at a higher risk to the adverse effects of extreme weather events.[152,155] These vulnerable populations could benefit from urban planning policies that ensure that new buildings, including homes, are constructed to resist extreme weather events.[197]

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PHOTO CREDITS

Introduction to chapter; tourists walking close to misters keeping cool during heat wave in Las Vegas, Nevada, as shown in top banner: ©Julie Jacobson/AP/Corbis

SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The key messages were developed during technical discussions and expert deliberation at a two-day meeting of the eight chapter Lead Authors, plus Susan Hassol and Daniel Glick, held in Boulder, Colorado May 8-9, 2012; through multiple technical discussions via six teleconferences from January through June 2012, and an author team call to finalize the Traceable Account draft language on Oct 12, 2012; and through other various communications on points of detail and issues of expert judgment in the interim. The author team also engaged in targeted consultations during multiple exchanges with Contributing Authors, who provided additional expertise on subsets of the key message. These discussions were held after a review of the technical inputs and associated literature pertaining to human health, including a literature review,[209] workshop reports for the Northwest and Southeast United States, and additional technical inputs on a variety of topics.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and diseases-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast United States. Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

Air Pollution:

The effects of decreased ozone air quality on human health have been well documented concerning projected increases in ozone,[6,7,9,11,39] even with uncertainties in projections owing to the complex formation chemistry of ozone and climate change, precursor chemical inventories, wildfire emission, stagnation episodes, methane emissions, regulatory controls, and population characteristics.[4] Ozone exposure leads to a number of health impacts.[1,2]

Allergens:

The effects of increased temperatures and atmospheric CO_2 concentration have been documented concerning shifts in flowering time and pollen initiation from allergenic plants, elevated production of plant-based allergens, and health effects of increased pollen concentrations and longer pollen seasons.[15,16,17,18,20,22,23,24,26,106] Additional studies have shown extreme rainfall and higher temperatures can lead to increased indoor air quality issues such as fungi and mold health concerns.[27]

Wildfire:

The effects of wildfire on human health have been well documented with increase in wildfire frequency[17,29,39,40] leading to decreased air quality[31,32,33] and negative health impacts.[32,34,36]

Temperature Extremes:

The effects of temperature extremes on human health have been well documented for increased heat waves,[51,53,54] which cause more deaths,[47,48] hospital admissions[50] and population vulnerability.[56,57]

Precipitation Extremes - Heavy Rainfall, Flooding, and Droughts:

The effects of weather extremes on human health have been well documented, particularly for increased heavy precipitation, which has contributed to increases in severe flooding events in certain regions. Floods are the second deadliest of all weather-related hazards in the United States.[63,64] Elevated waterborne disease outbreaks have been reported in the weeks following heavy rainfall,[65] although other variables may affect these associations.[66] Populations living in damp indoor environments experience increased prevalence of asthma and other upper respiratory tract symptoms.[67]

Disease Carried by Vectors:

Climate is one of the factors that influence the range of disease vectors; [73,74,76] a shift in the current range may increase interactions with people and affect human health.[71] North Americans are currently at risk from a number of vector-borne diseases.[75,82,83,85,86,87] There are some ambiguities on the relative role and contribution of climate change among the range of factors that affect disease transmission dynamics.[71,72,73,74,75,76] However, observational studies are already underway and confidence is high based on scientific literature that climate change has contributed to the expanded range of certain disease vectors, including *Ixodes* ticks which are vectors for Lyme disease in the United States.[78,84,89]

Food- and Waterborne Diarrheal Disease:
There has been extensive research concerning the effects of climate change on water- and food-borne disease transmission.[92,93,95,96,97] The current evidence base strongly supports waterborne diarrheal disease being both seasonal and sensitive to climate variability. There are also multiple studies associating extreme precipitation events with waterborne disease outbreaks.[65] This evidence of responsiveness of waterborne disease to weather and climate, combined with evidence strongly suggesting that temperatures will increase and extreme precipitation events will increase in frequency and severity (Ch. 2: Our Changing Climate), provides a strong argument for climate change impacts on waterborne disease by analogy. There are multiple studies associating extreme precipitation events with waterborne disease outbreaks and strong climatological evidence for increasing frequency and intensity of extreme precipitation events in the future. The scientific literature modeling the projected impacts of climate change on waterborne disease is somewhat limited, however. Combined, we therefore have overall medium confidence in the impact of climate change on waterborne and food-borne disease.

Harmful Algal Blooms:
Because algal blooms are closely related to climate factors, projected changes in climate could affect algal blooms and lead to increases in food- and waterborne exposures and subsequent cases of illness.[96,97,98,99,103] Harmful algal blooms have multiple exposure routes.[100]

Food Security:
Climate change is expected to have global impacts on both food production and certain aspects of food quality. The impact of temperature extremes, changes in precipitation and elevated atmospheric CO_2, and increasing competition from weeds and pests on crop plants are areas of active research (Ch. 6: Agriculture, Key Message 6).[105,106] The U.S. as a whole will be less affected than some other countries. However, the most vulnerable, including those dependent on subsistence lifestyles, especially Alaska Natives and low-income populations, will confront shortages of key foods.

Mental Health and Stress-Related Disorders:
The effects of extreme weather on mental health have been extensively studied.[120,122,123] Studies have shown the impacts of mental health problems after disasters,[124] with extreme events like Hurricane Katrina,[125] floods,[126] heat waves,[127] and wildfires[128] having led to mental health problems. Further work has shown that some people with mental illnesses are especially vulnerable to heat. Suicide rates vary with weather,[131,132] dementia is a risk factor for hospitalization and death during heat waves,[127,133] and medications for schizophrenia may interfere with temperature regulation or even directly cause hyperthermia.[134] Additional potential mental health impacts include distress associated with environmental degradation, displacement, and the knowledge of climate change.[122,123,136]

New information and remaining uncertainties
Important new evidence on heat-health effects[44,45] confirmed many of the findings from a prior literature review. Uncertainties in the magnitude of projections of future climate-related morbidity and mortality can result from differences in climate model projections of the frequency and intensity of extreme weather events such as heat waves and other climate parameters such as precipitation.

Efforts to improve the information base should address the coordinated monitoring of climate and improved surveillance of health effects.

Assessment of confidence based on evidence
Overall: **Very High** confidence. There is considerable consensus and a high quality of evidence in the published peer-reviewed literature that a wide range of health effects will be exacerbated by climate change in the United States. There is less agreement on the magnitude of these effects because of the exposures in question and the multi-factorial nature of climate-health vulnerability, with regional and local differences in underlying health susceptibilities and adaptive capacity. Other uncertainties include how much effort and resources will be put into improving the adap-

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

tive capacity of public health systems to prepare in advance for the health effects of climate change, prevent harm to individual and community health, and limit associated health burdens and societal costs.

Increased Ozone Exposure: **Very High** confidence.
Allergens: **High** confidence.
Wildfires: **Very High** confidence.
Thermal Extremes: **Very High** confidence.
Extreme Weather Events: **Very High** confidence.
Vector-borne Infectious Diseases: **High** or **Very High** confidence for shift in range of disease-carrying vectors. **Medium** confidence for whether human disease transmission will follow.
Food- and Waterborne disease: **Medium** confidence.
Harmful Algal Blooms: **Medium** confidence.
Food Security: **Medium** confidence for food quality; **High** confidence for food security.

Threats to Mental Health: **Very High** confidence for post-disaster impacts; **Medium** confidence for climate-induced stress.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Climate change will, absent other changes, amplify some of the existing health threats the nation now faces. Certain people and communities are especially vulnerable, including children, the elderly, the sick, the poor, and some communities of color.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast regions.[210] Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

Current epidemiological evidence on climate-sensitive health outcomes in the U.S. indicates that health impacts will differ substantially by location, pathway of exposure, underlying susceptibility, and adaptive capacity. These disparities in health impacts will largely result from differences in the distribution of individual attributes in a population that confers vulnerability (age, socioeconomic status, and race), attributes of place that reduce or amplify exposure (floodplain, coastal zone, and urban heat island), and the resilience of critical public health infrastructure.

Amplification of existing health threats: The effects of extreme heat and heat waves, projected worsening air pollution and asthma, extreme rainfall and flooding, and displacement and injuries associated with extreme weather events, fueled by climate change, are already substantial public health issues. Trends projected under a changing climate are projected to exacerbate these health effects in the future.[62]

Children: The effects of climate change increase vulnerability of children to extreme heat, and increased health damage (morbidity, mortality) resulting from heat waves has been well documented.[16,22,51,53,140] Extreme heat also causes more pediatric deaths,[47,48] and more emergency room visits and hospital admissions.[49,50] Adverse effects from increased heavy precipitation can lead to more pediatric deaths, waterborne diseases,[66] and illness.[141]

The elderly: Heat stress is especially damaging to the health of older people,[45,49,60,133,142,209] as are climate-sensitive increases in air pollution.

The sick: People and communities lacking the resources to adapt or to enhance mobility and escape health-sensitive situations are at relatively high risk.[164]

The poor: People and communities lacking the resources to adapt or to move and escape health-sensitive situations are at relatively high risk.[164]

Some communities of color: There are racial disparities in climate-sensitive exposures to extreme heat in urban areas, and in access to means of adaptation – for example air conditioning use.[149,151,157,211] There are also racial disparities in withstanding, and recovering from, extreme weather events.[155,162]

Climate change will disproportionately impact low-income communities and some communities of color, raising environmental justice concerns.[139,149,151,154,155,157,161,164] Existing health disparities[153,158,159] and other inequities[161] increase vulnerability. For example, Hurricane Katrina demonstrated how vulnerable these populations were to extreme weather events because many low-income and of-color New Orleans residents were killed, injured, or had difficulty evacuating and recovering from the storm.[155,162] Other climate change related issues that have an equity component include heat waves and air quality.[139,149,154,164]

New information and remaining uncertainties

Important new evidence[45] confirmed findings from a prior literature review.[139]

The potential for specific climate-vulnerable communities to experience highly harmful health effects is not entirely clear in specific regions and on specific time frames due to uncertainties in rates of adaptation and uncertainties about the outcome of public health interventions currently being implemented that aim to address underlying health disparities and determinants of health.[206] The public health community has not routinely conducted evaluations of the overall success of adaptation interventions or of particular elements of those interventions.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence that climate change will amplify existing health threats: **Very High**.
Among those especially vulnerable are:
Children: **Very High**.
The elderly: **Very High**.
The sick: **Very High**.
The poor: **Very High**.
Some communities of color: **High**.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Early action provides the largest health benefits. As threats increase, our ability to adapt to future changes may be limited.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast United States. Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

A number of studies have demonstrated that prevention activities that reduce carbon pollution, like using alternative energy sources[174] and using active transportation like biking or walking,[188] can lead to significant public health benefits, which can save costs in the near and long term.[176] Health impacts associated with climate change can be prevented through early action at significantly lower cost than dealing with them after they occur. For example, heat wave early warning systems are much less expensive than treating heat-related illnesses.[165] Existing adaptation programs have improved public health resilience.[9,153] One survey highlighted opportunities to address climate change preparedness activities and climate-health research[181] before needs become more widespread.

Considering U.S. public health in general, the cost-effectiveness of many prevention activities is well established.[183] Some preventive actions are cost-saving, while others are deemed cost-effective based on a pre-determined threshold. Early preventive interventions, such as early warnings for extreme weather, can be particularly cost-effective.[166] However, there is less information on the cost-effectiveness of specific prevention interventions relevant to climate sensitive health threats (for example, heat early warning systems). Overall, we have high confidence that public health actions can do much to protect people from some of the impacts of climate change, and that early action provides the largest health benefits.

The inverse relationship between the magnitude of an impact and a community's ability to adapt is well established and understood. Two extreme events, Hurricane Katrina and the European heat wave of 2003, illustrate this relationship well.[167] Extreme events interact with social vulnerability to produce extreme impacts, and the increasing frequency of extreme events associated with climate change is prompting concern for impacts that may overwhelm adaptive capacity.[62,173] This is equally true of the public health sector, specifically, leading to very high confidence that as threats increase, our ability to adapt to future changes may be limited.

New information and remaining uncertainties

A key issue (uncertainty) is the extent to which the nation, states, communities and individuals will be able to adapt to climate change because this depends on the levels of local exposure to climate-health threats, underlying susceptibilities, and the capacities to adapt that are available at each scale. Overall, the capacity of the American public health and health care delivery systems faces many challenges.[182] The cost of dealing with current health problems is diverting resources from preventing them in the first place. This makes the U.S. population more vulnerable.[56,183]

Steps for improving the information base on adaptation include undertaking a more comprehensive evaluation of existing climate-health preparedness programs and their effectiveness in various jurisdictions (cities, counties, states, nationally).

Assessment of confidence based on evidence

Overall, given the evidence base and remaining uncertainties: **High**.
High: Public health actions, especially preparedness and prevention, can do much to protect people from some of the impacts of climate change. Prevention provides the most protection; but we do not as yet have a lot of post-implementation information with which to evaluate preparedness plans.
High: Early action provides the largest health benefits. There is evidence that heat-health early warning systems have saved lives and money in U.S. cities like Philadelphia, PA.[165]
Very High: Our ability to adapt to future changes may be limited.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Responding to climate change provides opportunities to improve human health and well-being across many sectors, including energy, agriculture, and transportation. Many of these strategies offer a variety of benefits, protecting people while combating climate change and providing other societal benefits.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in several foundational technical inputs prepared for this chapter, including a literature review[209] and workshop reports for the Northwest and Southeast U.S. regions.[210] Nearly 60 additional technical inputs related to human health were received and reviewed as part of the Federal Register Notice solicitation for public input.

A number of studies have explored the opportunities available to improve health and well-being as a result of adapting to climate change,[176] with many recent publications illustrating the benefit of reduced air pollution.[6,174,175,195] Additionally, some studies have looked at the co-benefits to climate change and health of applying innovative urban design practices which reduce energy consumption and pollution while increasing public health,[99,188,197,198] decrease vulnerability of communities to extreme events[152,197] and reduce the disparity between different societal groups.[206,207,212]

New information and remaining uncertainties

More studies are needed to fully evaluate both the intended and unintended health consequences of efforts to improve the resiliency of communities and human infrastructure to climate change impacts. There is a growing recognition that the magnitude of these health co-benefits or co-harms could be significant, both from a public health and an economic standpoint. [176,188,189]

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **Very High**.


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Climate Change Impacts in the United States

CHAPTER 10
ENERGY, WATER, AND LAND USE

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

10 ENERGY, WATER, AND LAND USE

KEY MESSAGES

1. **Energy, water, and land systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate change vulnerability as well as adaptation and mitigation options for different regions of the country.**
2. **The dependence of energy systems on land and water supplies will influence the development of these systems and options for reducing greenhouse gas emissions, as well as their climate change vulnerability.**
3. **Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is challenging, but can improve the identification and evaluation of options for reducing climate change impacts.**

Energy, water, and land systems interact in many ways. Energy projects (energy production and delivery) require varying amounts of water and land; water projects (water supply and irrigation) require energy and land; and land-based activities (agriculture and forestry) depend upon energy and water. Increasing population and a growing economy intensify these interactions.[1] Each sector is directly impacted by the others and by climate change, and each sector is a target for adaptation and mitigation efforts. Better understanding of the connections between and among energy, water, and land systems can improve our capacity to predict, prepare for, and mitigate climate change.

Challenges from climate change will arise from long-term, gradual changes, such as sea level rise, as well as from projected changes in weather extremes that have more sudden impacts. The independent implications of climate change for the energy, water, and land sectors have been studied extensively (see Ch. 4: Energy, Ch. 3: Water, and Ch. 13: Land Use & Land Cover Change). However, there are few analyses that capture the interactions among and competition for resources within these three sectors.[1] Very little information is available to evaluate the implications for decision-making and planning, including legal, social, political, and other decisions.

Energy, Water, Land, and Climate Interactions

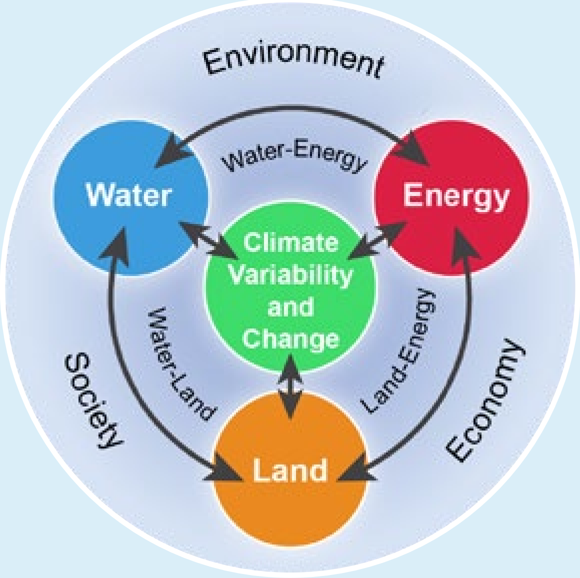


Figure 10.1. The interactions between and among the energy, water, land, and climate systems take place within a social and economic context. (Figure source: Skaggs et al. 2012[1]).

Climate change is not the only factor driving changes. Other environmental and socioeconomic stressors interact with climate change and affect vulnerability and response strategies with respect to energy, water, and land systems. The availability and use of energy, water, and land resources and the ways in which they interact vary across the nation. Regions in the United States differ in their 1) energy mix (solar, wind, coal, geothermal, hydropower, nuclear, natural gas, petroleum, ethanol); 2) observed and projected precipitation and temperature patterns; 3) sources and quality of available water resources (for example, ground, surface, recycled); 4) technologies for storing, transporting, treating and using water; and 5) land use and land cover (see Ch. 13: Land Use & Land Cover Change). Decision-making processes for each sector also differ, and decisions often transcend scales, from local to state to federal, meaning that mitigation and adaptation options differ widely.

Given the many mitigation and adaptation opportunities available through the energy sector, a focus on energy is a useful way to highlight the interactions among energy, water, and land as well as intersections with climate and other stressors. For example, energy production already competes for water resources with agriculture, direct human uses, and natural systems. Climate-driven changes in land cover and land use are projected to further affect water quality and availability, increasing the competition for water needed for energy production. In turn, diminishing water quality and availability means that there will be a need for more energy to purify water and more infrastructure on land to store and distribute water. Stakeholders need to understand the interconnected nature of climate change impacts, and the value of assessments would be improved if risks and vulnerabilities were evaluated from a cross-sector standpoint.[2]

Key Message 1: Cascading Events

Energy, water, and land systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate change vulnerability as well as adaptation and mitigation options for different regions of the country.

Energy production, land use, and water resources are linked in increasingly complex ways. In some parts of the country, electric utilities and energy companies compete with farmers and ranchers, other industries, and municipalities for water rights and availability, which are also constrained by interstate and international commitments. Private and public sector decision-makers must consider the impacts of strained water supplies on agricultural, ecological, industrial, urban, and public health needs. Across the country, these intertwined sectors will witness increased stresses due to climate changes that are projected to lower water quality and/or quantity in many regions and change heating and cooling electricity demands.

Coast-to-Coast 100-degree Days in 2011

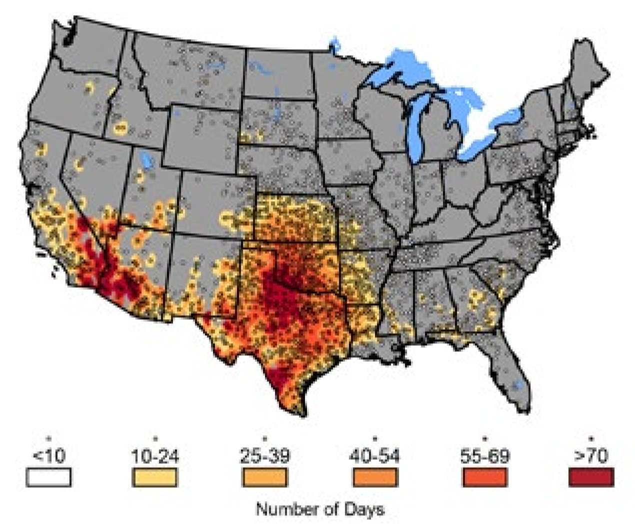


Figure 10.2. Map shows numbers of days with temperatures above 100°F during 2011. The black circles denote the location of observing stations recording 100°F days. The number of days with temperatures exceeding 100°F is expected to increase. The record temperatures and drought during the summer of 2011 represent conditions that will be more likely in the U.S. as climate change continues. When outdoor temperatures increase, electricity demands for cooling increase, water availability decreases, and water temperatures increase. Alternative energy technologies may require little water (for example, solar and wind) and can enhance resilience of the electricity sector, but still face land-use and habitat considerations. The projected increases in drought and heat waves provide an example of the ways climate changes will challenge energy, water, and land systems. (Figure source: NOAA NCDC, 2012).

The links between and among energy, water, and land sectors mean that they are susceptible to cascading effects from one sector to the next. An example is found in the drought and heat waves experienced across much of the U.S. during the summers of 2011 and 2012. In 2011, drought spread across the south-central U.S., causing a series of energy, water, and land impacts that demonstrate the connections among these sectors. Texans, for example, experienced the hottest and driest summer on record. Summer average temperatures were 5.2°F higher than normal, and precipitation was lower than previous records set in 1956. The associated heat wave, with temperatures above 100°F for 40 consecutive days, together with drought, strained the region's energy and water resources.[3,4,5]

These extreme climate events resulted in cascading effects across energy, water, and land systems. High temperatures caused increased demand for electricity for air conditioning, which corresponded to increased water withdrawal and consumption for electricity generation. Heat, increased evaporation, drier soils, and lack of rain led to higher irrigation demands, which added stress on water resources required for energy production. At the same time, low-flowing and warmer rivers threatened to suspend power plant production in several locations, reducing the options for dealing with the concurrent increase in electricity demand.

The impacts on land resources and land use were dramatic. Drought reduced crop yields and affected livestock, costing Texas farmers and ranchers more than $5 billion, a 28% loss compared to average revenues of the previous four years.[6] With increased feed costs, ranchers were forced to sell livestock at lower profit. Drought increased tree mortality,[7] providing more fuel for record wildfires that burned 3.8 million acres (an area about the size of Connecticut) and destroyed 2,763 homes.[8]

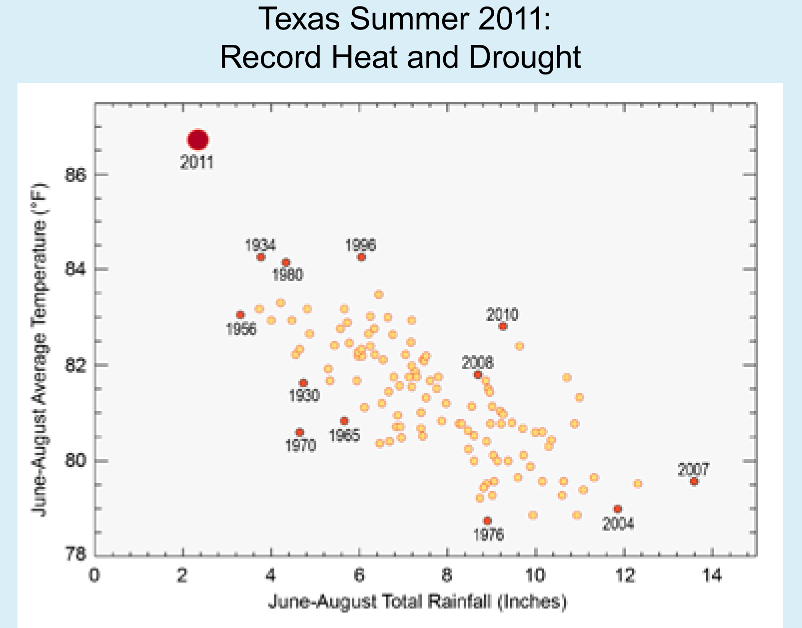


Figure 10.3. Graph shows average summer temperature and total rainfall in Texas from 1919 through 2012. The red dots illustrate the range of temperatures and rainfall observed over time. The record temperatures and drought during the summer of 2011 (large red dot) represent conditions far outside those that have occurred since the instrumental record began.[4] An analysis has shown that the probability of such an event has more than doubled as a result of human-induced climate change[3]. (Figure source: NOAA NCDC / CICS-NC).

Energy, water, and land interactions complicated and amplified the direct impacts on the electric sector. With electricity demands at all-time highs, water shortages threatened more than 3,000 megawatts of generating capacity – enough power to supply more than one million homes.[9] As a result of the record demand and reduced supply, marginal electricity prices repeatedly hit $3,000 a megawatt hour, which is three times the maximum amount that generators can charge in deregulated electricity markets in the eastern United States.[10]

Competition for water also intensified. More than 16% of electricity production relied on cooling water from sources that shrank to historically low levels,[9] and demands for water used to generate electricity competed with simultaneous demands for agriculture and other human activities. City and regional managers rationed water to farms and urban areas, and in some instances, water was trucked to communities that lacked sufficient supplies.[11] As late as January 2012, customers of 1,010 Texas water systems were being asked to restrict water use; mandatory water restrictions were in place in 647 water systems.[12] At the same time, changing vegetation attributes, grazing, cropping, and wildfire compromised water quality and availability, increasing the amount of power required for water pumping and purification.

The Texas example shows how energy, land, water, and weather interacted in one region. Extreme weather events may affect other regions differently, because of the relative vulnerability of energy, water, and land resources, linkages, and infrastructure. For example, sustained droughts in the Northwest will affect how water managers release water from reservoirs, which in turn will affect water deliveries for ecosystem services, irrigation, recreation, and hydropower. Further complicating matters, hydropower is increasingly being used to balance variable wind generation in the Northwest, and seasonal hydroelectric restrictions have already created challenges to fulfilling this role. In the Midwest, drought poses challenges to meeting electricity demands because diminished water availability and elevated water temperatures reduce the efficiency of electricity generation by thermoelectric power plants. To protect water quality, federal and state regulations can require suspension of operations of thermoelectric power plants if water used to cool the power plants exceeds established temperature thresholds as it is returned to streams.

Energy, land, water, and weather interactions are not limited to drought. For instance, 2011 also saw record flooding in the Mississippi basin. Floodwaters surrounded the Fort Calhoun nuclear power plant in Nebraska, shut down substations, and caused a wide range of energy, land, and water impacts (Ch. 3: Water).

Interactions of Energy, Water, and Land Uses

Figure 10.4 depicts the current mix of energy, water, and land use within each U.S. region. The mixes reflect competition for water and land resources, but more importantly for the purposes here, the mixes reflect linkages across the energy, water, and land sectors as well as linkages to climate. For example, higher water withdrawal for thermoelectric power (power plants that use a steam cycle to generate electricity) generally reflects electric generation technology choices (often coal-, gas-, or nuclear-fired generation with open loop cooling) that assume the availability of large quantities of water. Therefore, the choice of energy technology varies based on the available resources in a region. Similarly, land-water linkages are evident in cropland and agricultural water use. The potential growth in renewable energy may strengthen the linkage between energy and land (see "Examples of Energy, Water, and Land Linkages"). Climate change affects each sector directly and indirectly. For instance, climate change affects water supplies, energy demand, and land productivity, all of which can affect sector-wide decisions.

Regional Water, Energy, and Land Use, with Projected Climate Change Impacts

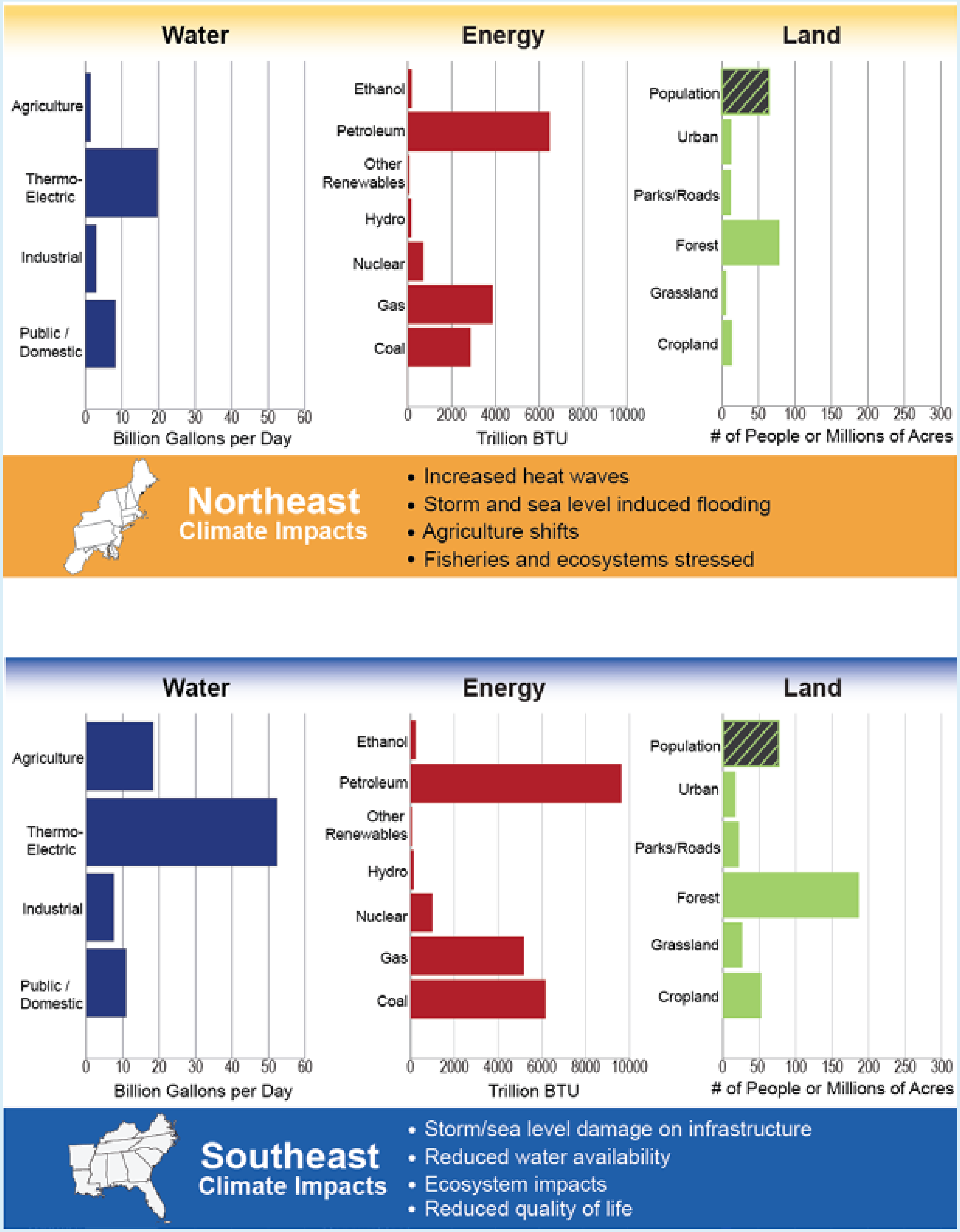
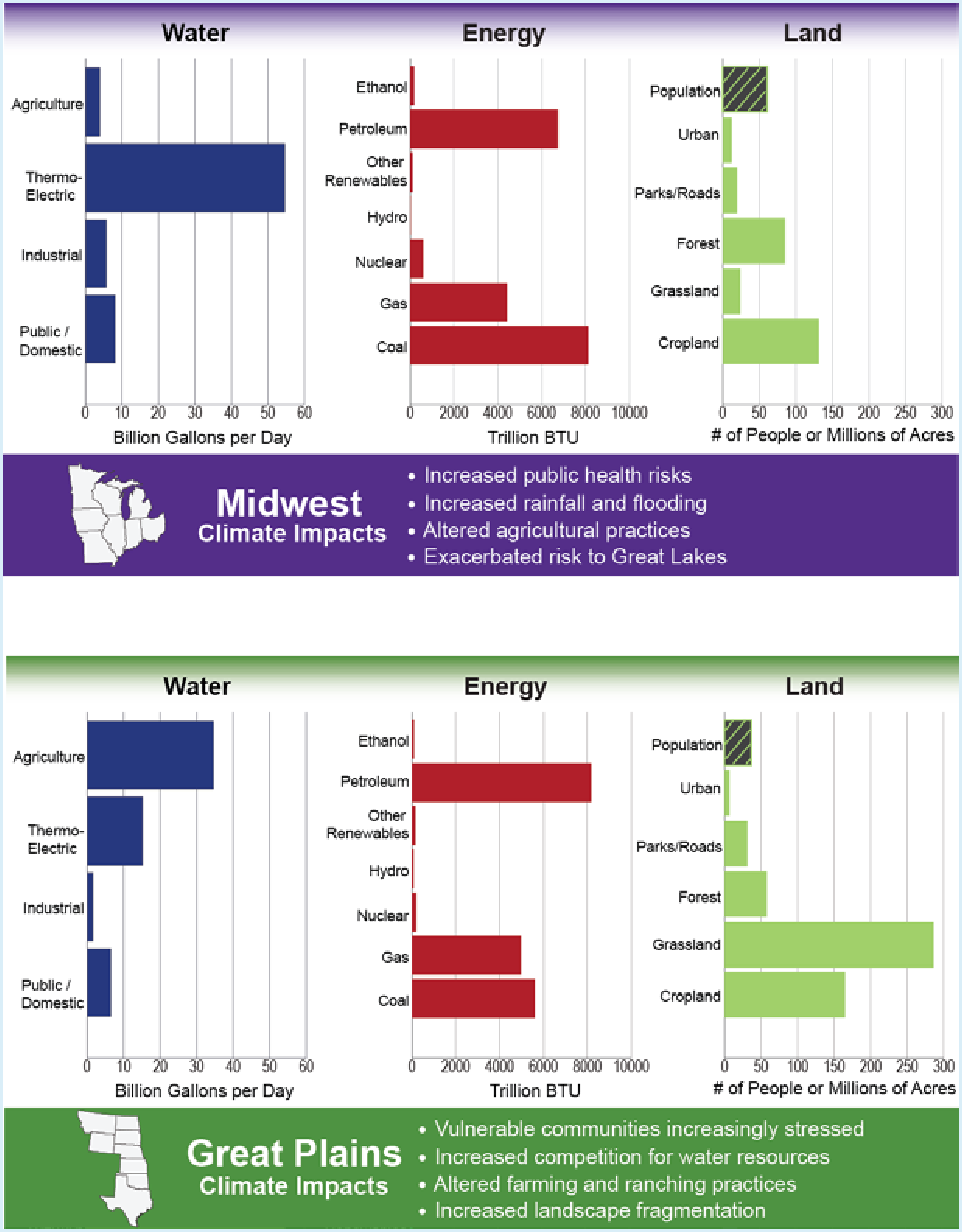


Figure 10.4. U.S. regions differ in the manner and intensity with which they use, or have available, energy, water, and land. Water bars represent total water withdrawals in billions of gallons per day (except Alaska and Hawai'i, which are in millions of gallons per day); energy bars represent energy production for the region in 2012; and land represents land cover by type (green bars) or number of people (black and green bars). Only water withdrawals, not consumption, are shown (see Ch. 3: Water). Agricultural water withdrawals include irrigation, livestock, and aquaculture uses. (Data from EIA 2012[13] [energy], Kenny et al. 2009[14] [water], and USDA ERS 2007[15] [land]).

Regional Water, Energy, and Land Use, with Projected Climate Change Impacts



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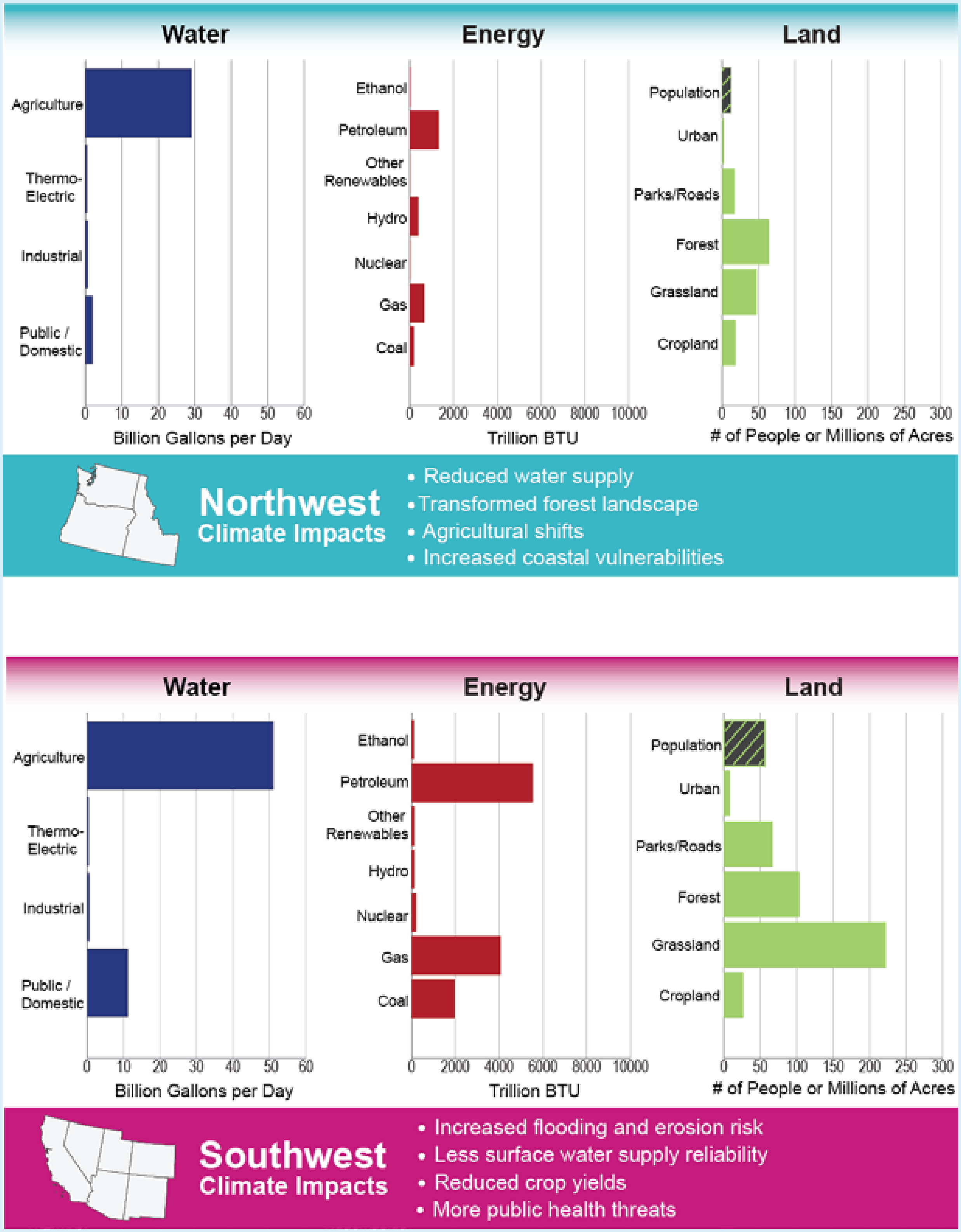

Regional Water, Energy, and Land Use, with Projected Climate Change Impacts

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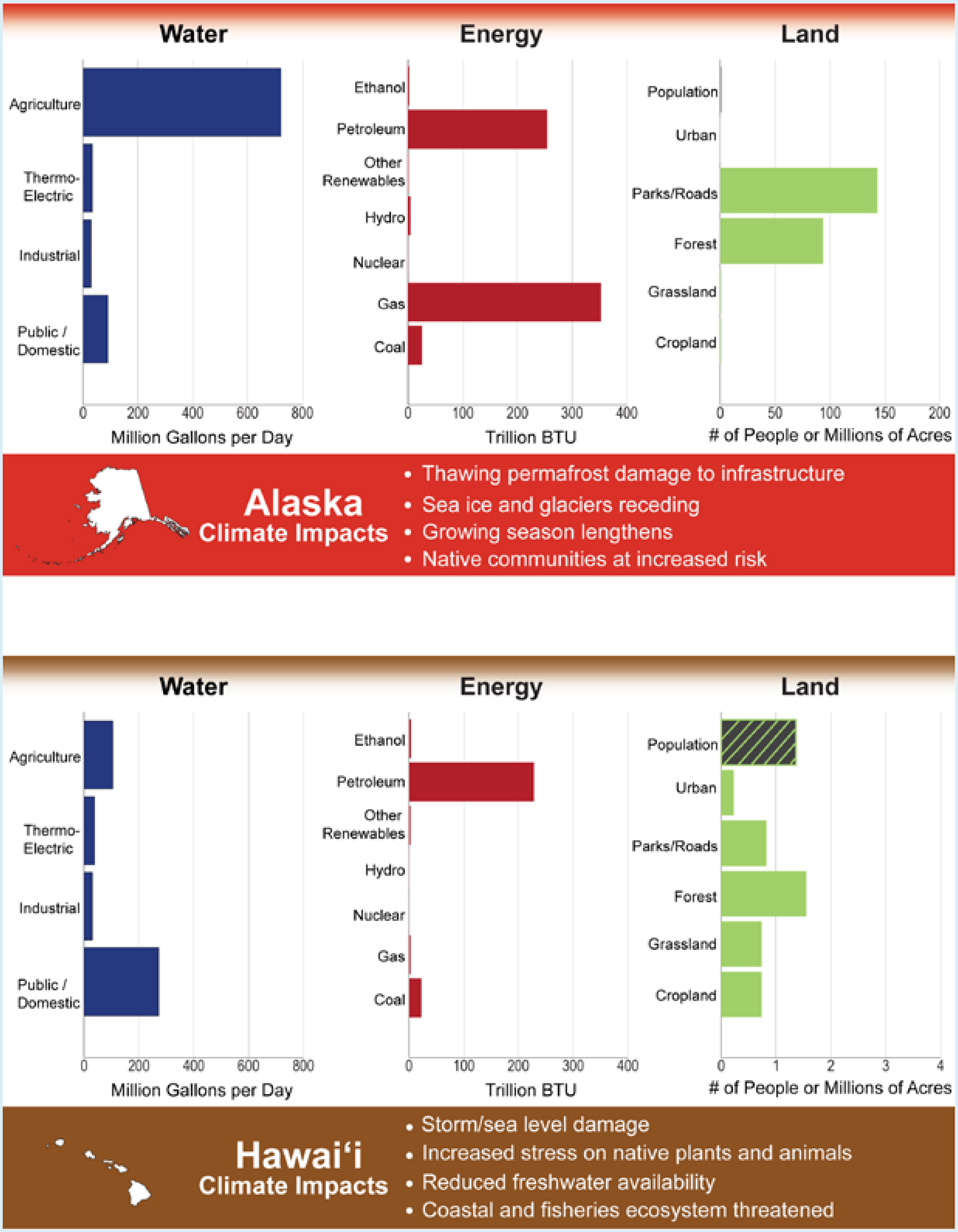
Regional Water, Energy, and Land Use, with Projected Climate Change Impacts



Alaska Climate Impacts

- Thawing permafrost damage to infrastructure
- Sea ice and glaciers receding
- Growing season lengthens
- Native communities at increased risk

Hawai‘i Climate Impacts

- Storm/sea level damage
- Increased stress on native plants and animals
- Reduced freshwater availability
- Coastal and fisheries ecosystem threatened

Figure 10.4. U.S. regions differ in the manner and intensity with which they use, or have available, energy, water, and land. Water bars represent total water withdrawals in billions of gallons per day (except Alaska and Hawai‘i, which are in millions of gallons per day); energy bars represent energy production for the region in 2012; and land represents land cover by type (green bars) or number of people (black and green bars). Only water withdrawals, not consumption, are shown (see Ch. 3: Water). Agricultural water withdrawals include irrigation, livestock, and aquaculture uses. (Data from EIA 2012[13] [energy], Kenny et al. 2009[14] [water], and USDA ERS 2007[15] [land]).

Key Message 2: Options for Reducing Emissions and Climate Vulnerability

The dependence of energy systems on land and water supplies will influence the development of these systems and options for reducing greenhouse gas emissions, as well as their climate change vulnerability.

Interactions among energy, water, and land resources have influenced and will continue to influence selection and operation of energy technologies. In some situations, land and water constraints also pose challenges to technology options for reducing

Water Use for Electricity Generation by Fuel and Cooling Technology

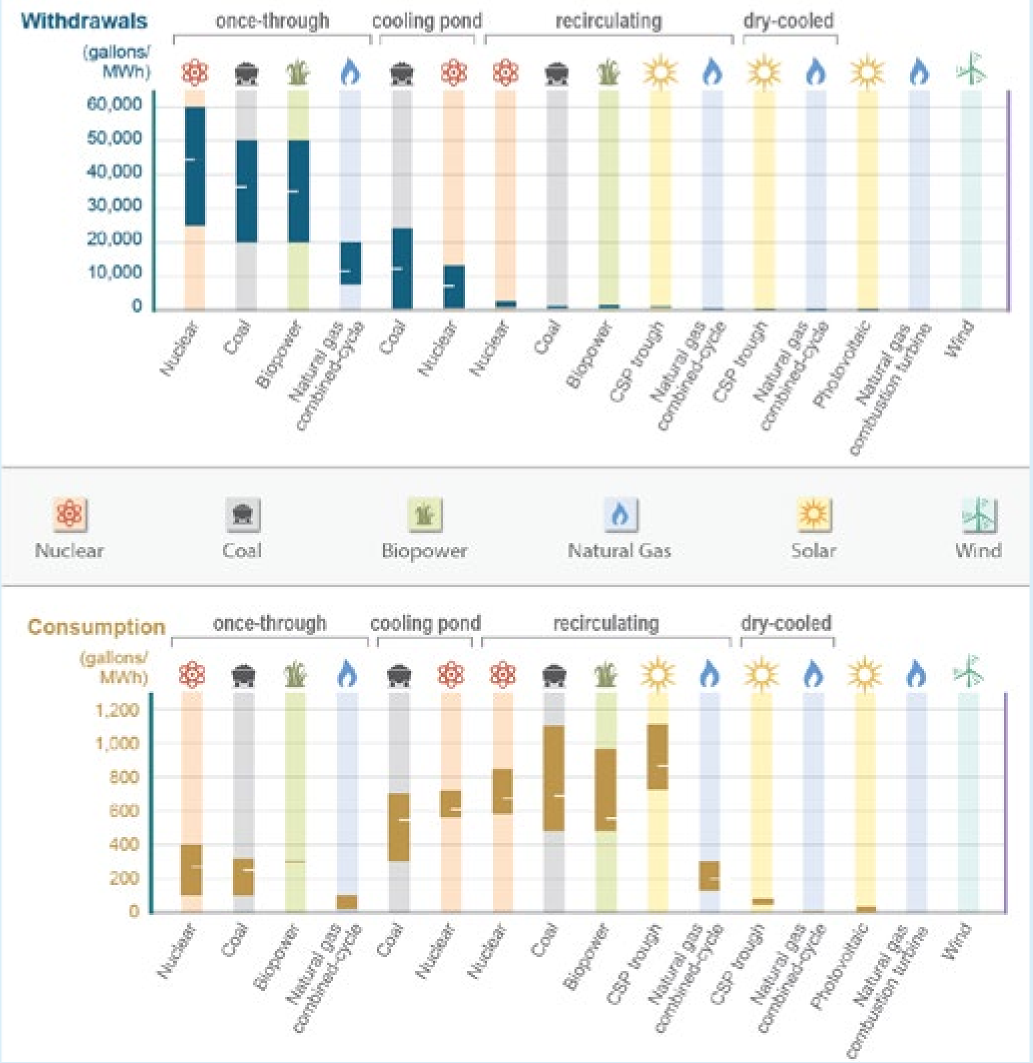


Figure 10.5. Technology choices can significantly affect water and land use. These two panels show a selection of technologies. Ranges in water withdrawal/consumption reflect minimum and maximum amounts of water used for selected technologies. Carbon dioxide capture and storage (CCS) is not included in the figures, but is discussed in the text. The top panel shows water withdrawals for various electricity production methods. Some methods, like most conventional nuclear power plants that use "once-through" cooling systems, require large water withdrawals but return most of that water to the source (usually rivers and streams). For nuclear plants, utilizing cooling ponds can dramatically reduce water withdrawal from streams and rivers, but increases the total amount of water consumed. Beyond large withdrawals, once-through cooling systems also affect the environment by trapping aquatic life in intake structures and by increasing the temperature of streams.[18] Alternatively, once-through systems tend to operate at slightly better efficiencies than plants using other cooling systems. The bottom panel shows water consumption for various electricity production methods. Coal-powered plants using recirculating water systems have relatively low requirements for water withdrawals, but consume much more of that water, as it is turned into steam. Water consumption is much smaller for various dry-cooled electricity generation technologies, including for coal, which is not shown. Although small in relation to cooling water needs, water consumption also occurs throughout the fuel and power cycle.[19] (Figure source: Averyt et al. 2011[20]).

greenhouse gas emissions. For example, with the Southwest having most of the potential for deployment of concentrating solar technologies, facilities will need to be extremely water-efficient in order to compete for limited water resources. While wind farms avoid impacts on water resources, issues concerning land use, wildlife impacts, the environment, and aesthetics are often encountered. Raising crops to produce biofuels uses arable land and water that might otherwise be available for food production. This fact came into stark focus during the summer of 2012, when drought caused poor corn harvests, intensifying concerns about allocation of the harvest for food versus ethanol.[16]

Competition for water supplies is encouraging deployment of technologies that are less water-intensive than coal or nuclear power with once-through cooling. For example, wind, natural gas, photovoltaic (solar electric), and even thermoelectric generation with dry cooling use less water. Challenges in siting land- and water-intensive energy facilities are likely to intensify over time as competition for these resources grows. Considering the interactions among energy, water, and land systems presents opportunities for further identification and implementation of energy options that can reduce emissions, promote resilience, and improve sustainability.

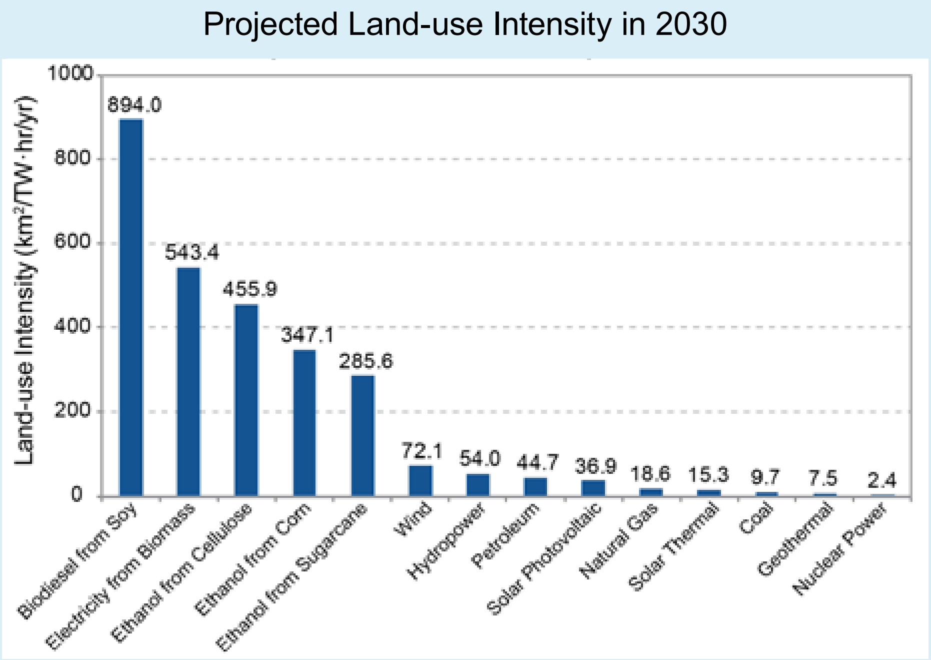


Figure 10.6. The figure shows illustrative projections for 2030 of the total land-use intensity associated with various electricity production methods. Estimates consider both the footprint of the power plant as well as land affected by energy extraction. There is a relatively large range in impacts across technologies. For example, a change from nuclear to wind power could mean a significant change in associated land use. For each electricity production method, the figure shows the average of a most-compact and least-compact estimate for how much land will be needed per unit of energy. The figure uses projections from the Energy Information Administration Reference scenario for the year 2030, based on energy consumption by fuel type and power plant "capacity factors" (the ratio of total power generation to maximum possible power generation). The most-compact and least-compact estimates of biofuel land-use intensities reflect differences between current yield and production efficiency levels and those that are projected for 2030 assuming technology improvements.[21] (Figure source: adapted from McDonald et al. 2009[21]).

Every option for reducing greenhouse gas emissions involves tradeoffs that affect natural resources, socioeconomic systems, and the built environment. Energy system technologies vary widely in their carbon emissions and their use of water and land. As such, there are energy-water-land tradeoffs and synergies with respect to adaptation and mitigation. Each choice involves assessing the relative importance of the tradeoffs related to these resources in the context of both short- and long-term risks (see "Examples of Energy, Water, and Land Linkages" that describes four technologies that could play key roles). Figure 10.5 provides a systematic comparison of water withdrawals and consumptive use, illustrating the wide variation across both electric generation technologies and the accompanying cooling technologies. Carbon dioxide capture and storage (CCS) is not included in the chart, but coal-fired


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Table 10.1. Energy, water, and land sectoral impacts associated with a sample of climate mitigation and adaptation measures. Plus sign means a positive effect (reduced stress) on sector, minus sign means a negative effect (increased stress) on sector. Blank means effect not noted. Blue means consideration of energy extraction and power plant processes. It is important to keep in mind that this table only reflects physical synergies and tradeoffs. There are, of course, economic tradeoffs as well in the form of technology costs and societal concerns, such as energy security, food security, and water quality. Expansion of hybrid or dry-cooled solar technologies, versus wet, could help reduce water risks. For a more detailed description of the entries in the table, see Skaggs et al. 2012.[1] Additional considerations regarding energy extraction, power plant processes, and energy use associated with irrigation were added to those reflected in Skaggs et al. 2012[1] (Adapted from Skaggs et al. 2012[1]).

Mitigation measures	Water	Land	Energy
Switch from coal to natural gas fueled power plants	+ and –	+ and –	
Expand CCS to fossil-fueled power plant	–	–	
Expansion of nuclear power	–		
Expansion of wind	+	–	
Expansion of solar thermal technologies (wet cooled)	–	–	
Expansion of commercial scale photovoltaic	+	–	
Expansion of hydropower	+ and –	–	+
Expansion of biomass production for energy	+ and –	+ and –	
Adaptation measures	**Water**	**Land**	**Energy**
Switch from once-through to recirculating cooling in thermoelectric power plants	+ and –		-
Switch from wet to dry cooling at thermoelectric power plants	+		-
Desalinization	+ and –	+	+ and –
New storage and conveyance of water	+ and –	–	–
Switch to drought-tolerant crops in drought vulnerable regions	+	–	+
Increase transmission capacity to urban areas to reduce power outages during high demand periods		–	+

power plants (both evaporative cooling and dry cooling) fitted with CCS would consume twice as much water per unit of electricity generated as similar coal-fired facilities without CCS.[17] Figure 10.6 shows projected land-use intensity in 2030 for various electricity production methods. Describing land use with a single number is valuable, but must be considered with care. For example, while wind generation can require significant amounts of land, it can co-exist with other activities such as farming and grazing, while other technologies may not be compatible with other land uses. Land and water influences on energy production capacity are expected to get stronger in the future, and greater resource scarcity will shape investment decisions.

Every adaptation and mitigation option involves tradeoffs in how it increases or decreases stress on energy systems and water and land resources. For a selected set of mitigation and adaptation measures, Table 10.1 provides a summary illustrating qualitatively how different technologies relate to energy, water, and land.[1]

Particularly relevant to climate change mitigation are the energy, water, and land risks associated with low-carbon electricity generation. For example, expansion of nuclear power and coal power with CCS are two measures that have been discussed as a potential part of a future decarbonized energy system.[22,23] Both are also potentially water intensive and therefore have vulnerabilities related to climate impacts and competing water uses. Alternatively, renewable generation and combined cycle gas and coal have relatively modest water withdrawals (see also EPRI 2011[24]). Overall, energy, water, and land sector vulnerabilities are important factors to weigh in considering alternative electricity generation options and cooling systems.

Bioenergy also presents opportunities for mitigation, but some potential bioenergy feedstocks are land and water intensive. Where land and water resources are limited, bioenergy may therefore be at risk of competing with other uses of land and water, and climate changes present additional challenges. Other mitigation options, such as afforestation (re-establishment of forests), forest management, agricultural soil management, and fertilizer management are also tied intimately into the interfaces among land availability, land management, and water resource quantity and quality.[25]

Some sector-specific mitigation and adaptation measures can provide opportunities to enhance climate mitigation or adaptation objectives in the other sectors. However, other measures may have negative impacts on mitigation or adaptation potential in other sectors. If such cross-sector impacts are not considered, they can diminish the effectiveness of climate mitigation and adaptation actions.


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For example, switching from coal- to natural-gas-fired electricity generation reduces the emissions associated with power generation. Depending on the situation, the switch to natural gas in the energy sector can either improve or reduce adaptive capacity in the water sector. Natural gas can reduce water use for thermoelectric cooling (gas-fired plants require less cooling water), but natural gas extraction techniques consume water, so water availability must be considered. In addition, gas production has the potential to affect land-based ecosystems by, for example, fragmenting habitat and inhibiting wildlife migration. Future improvements in natural gas technologies and water reuse may reduce the possibility of negative impacts on water supplies and enhance the synergies across the energy, water, and land interface. Incorporating consideration of such cross-sector interactions in planning and policy could affect sectoral decisions and decisions related to climate mitigation and adaptation.

Changes in the availability of water and land due to climate change and other effects of human activities will affect location, design, choice, and operations of energy technologies in the future and, in some cases, constrain their deployment. Energy, water, and land linkages represent constraints, risks, and opportunities for private/public planning and investment decisions. “Examples of Energy, Water, and Land Linkages” below discusses four energy sector technologies that could contribute to reducing U.S. emissions of greenhouse gases and increasing energy security – natural gas from shale, solar power, biofuels, and CCS. These technologies were chosen to illustrate energy, water, and land linkages and other complexities for the design, planning, and deployment of our energy future.

EXAMPLES OF ENERGY, WATER, AND LAND LINKAGES

Shale Natural Gas and Hydraulic Fracturing

The U.S. Energy Information Administration projects a 29% increase in U.S. natural gas production by 2035, driven primarily by the economics of shale gas.[13] As an energy source, natural gas (methane) can have a major advantage over coal and oil: when combusted, it emits less carbon dioxide per unit energy than other fossil fuels, and fewer pollutants like black carbon (soot) and mercury (see Ch. 27: Mitigation). An increase in natural gas consumption could lead to a reduction in U.S. greenhouse gas emissions compared to continued use of other fossil fuels. Disadvantages include the possibility that low-cost gas could supplant deployment of low-carbon generation technologies, such as nuclear power and renewable energy. In addition, the U.S. Environmental Protection Agency estimates that 6.9 million megatons of methane – with a global warming potential equivalent to 144.7 million megatons of CO_2 – is emitted from the U.S. natural gas system through uncontrolled venting and leaks from drilling operations, pipelines, and storage tanks (see Ch. 15: Biogeochemical Cycles; Ch. 27: Mitigation).[26] There is considerable uncertainty about these estimates, and it is an active area of research. While technological improvements may reduce this leakage rate,[26] leakage makes the comparison between natural gas and coal more complex from a climate perspective.[27] For example, methane is a stronger greenhouse gas than carbon dioxide but has a much shorter atmospheric lifetime (see Ch. 15: Biogeochemical Cycles; Ch. 27: Mitigation; Appendix 3: Climate Science; Appendix 4: FAQs).

Hydraulic Fracturing and Water Use

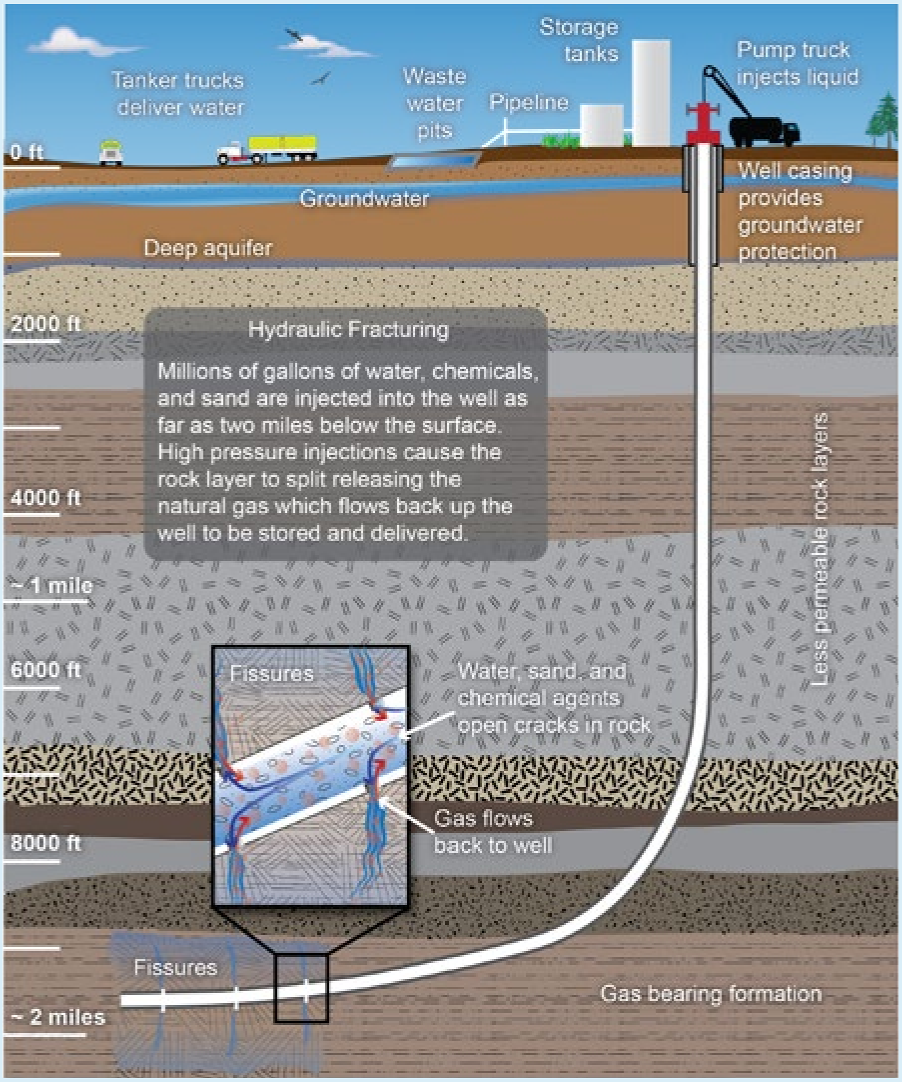

Figure 10.7. Hydraulic fracturing, a drilling method used to retrieve deep reservoirs of natural gas, uses large quantities of water, sand, and chemicals that are injected at high pressure into horizontally-drilled wells as deep as 10,000 feet below Earth's surface. The pressurized mixture causes the rock layer to crack. Sand particles hold the fissures open so that natural gas from the shale can flow into the well. Questions about the water quantity necessary for this extraction method as well as the potential to affect water quality have produced national debate. (Figure source: NOAA NCDC).

Recent reductions in natural gas prices are largely due to advances in hydraulic fracturing, which is a drilling method used to retrieve deep reservoirs of natural gas. Hydraulic fracturing injects large quantities of water, sand, and chemicals at high pressure into horizontally-drilled wells as deep as 10,000 feet below the surface in order to break the shale and extract natural gas.[28] Questions about the water quantity necessary and the potential to affect water quality have produced national

Continued

EXAMPLES OF ENERGY, WATER, AND LAND LINKAGES (CONTINUED)

debate about this method. Federal government and state-led efforts are underway to identify, characterize, and if necessary, find approaches to address these issues (for example, EPA 2011; FracFocus 2012[29]).

A typical shale gas well requires from two to four million gallons of water to drill and fracture (equivalent to the annual water use of 20 to 40 people in the U.S, or three to six Olympic-size swimming pools).[28] The gas extraction industry has begun reusing water in order to lower this demand. However, with current technology, recycling water can require energy-intensive treatment, and becomes more difficult as salts and other contaminants build up in the water with each reuse.[30] In regions where climate change leads to drier conditions, hydraulic fracturing could be vulnerable to climate change related reductions in water supply.

Shale gas development also requires land. To support the drilling and hydraulic fracturing process, a pad, which may be greater than five acres in size, is constructed.[31] Land for new roads, compressor stations, pipelines, and water storage ponds are also required.

The competition for water is expected to increase in the future. State and local water managers will need to assess how gas extraction competes with other priorities for water use, including electricity generation, irrigation, municipal supply, industry use, and livestock production. Collectively, such interactions between the energy and water resource sectors increase vulnerability to climate change, particularly in water-limited regions that are projected to, or become, significantly drier.

Solar Power Generation

Solar energy technologies have the potential to satisfy a significant portion of U.S. electricity demand and reduce greenhouse gas emissions. The land and water requirements for solar power generation depend on the mix of solar technologies deployed. Small-scale (such as rooftop) installations are integrated into current land use and have minimal water requirements. In contrast, utility-scale solar technologies have significant land requirements and can – depending upon the specific generation and cooling technologies – also require significant water resources. For instance, utility-scale photovoltaic systems can require three to ten acres per megawatt (MW) of generating capacity[32] and consume as much as five gallons of water per megawatt hour (MWh) of electricity production. Utility-scale concentrating solar systems can require up to 15 acres per MW[33] and consume 1,040 gallons of water per MWh[34] using wet cooling (and 97% less water with dry cooling). A recent U.S. Department of Energy study concluded that 14% of the U.S. demand for electricity could be met with solar power by 2030.[34] To generate that amount of solar power would require rooftop installations plus about 0.9 million to 2.7 million acres, equivalent to about 1% to 4% of the land area of Arizona, for utility-scale solar power systems and concentrating solar power (CSP).[34]

Renewable Energy and Land Use

Figure 10.8. Photovoltaic panels convert sunlight directly into electricity. Utility-sized solar power plants require large tracts of land. Photo shows Duke Energy's 113-acre Blue Wing Solar Project in San Antonio, Texas, one of the largest photovoltaic solar farms in the country. (Photo credit: Duke Energy 2010[36]).

Recognizing water limitations, most large-scale solar power systems now in planning or development are designed with dry cooling that relies on molten salt or other materials for heat transfer. However, while dry cooling systems reduce the need for water, they have lower plant thermal efficiencies, and therefore reduced production on hot days.[35] Overall, as with other generation technologies, plant designs will have to carefully balance cost, operating issues, and water availability.

Biofuels

Biomass-based energy is currently the largest renewable energy source in the U.S., and biofuels from crops, grass, and trees are the fastest growing renewable domestic bioenergy sector.[13] In 2011, approximately 40 million acres of cropland in the U.S. were used for ethanol production, roughly 16% of the land planted for the eight major field crops.[37] The long-term environmental and social effects of biofuel production and use depend on many factors: the type of feedstock, manage-

Continued

EXAMPLES OF ENERGY, WATER, AND LAND LINKAGES (CONTINUED)

ment practices used to produce them, fuel production and conversion technologies, prior land use, and land- and water-use changes caused by their production and use.[38,39] Biofuels potentially can reduce greenhouse gas emissions by displacing fossil fuel consumption. Biofuels that comply with the Energy Independence and Security Act of 2007 are required to reduce greenhouse gas emissions relative to fossil fuels. In addition, biofuels also have the potential to provide net environmental benefits compared to fossil fuels. For example, ethanol is used as a gasoline additive to meet air quality standards, replacing a previous additive that leaked from storage tanks and contaminated groundwater.[40] However, increases in corn production for biofuel has been cited as contributing to harmful algal blooms.[38]

Currently, most U.S. biofuels, primarily ethanol (from corn) and biodiesel (mainly from soy), are produced from edible parts of crops grown on rain-fed land. Consumptive water use over the life cycle of corn-grain ethanol varies widely, from 15 gallons of water per gallon of gasoline equivalent for rain-fed corn-based ethanol in Ohio, to 1,500 gallons of water per gallon of gasoline equivalent for irrigated corn-based ethanol in New Mexico. In comparison, producing and refining petroleum-based fuels uses 1.9 to 6.6 gallons of water per gallon of gasoline.[38,41]

The U.S. Renewable Fuels Standard (RFS) aims to expand production of cellulosic ethanol to at least 16 billion gallons per year by 2022. Cellulosic biofuels, derived from the entire plant rather than just the food portions, potentially have several advantages, such as fewer water quality impacts,[42] less water consumption, and the use of forest-derived feedstocks.[38] Cellulosic biofuels have not yet been produced in large volumes in the United States. The RFS target could require up to an additional 30 to 60 million acres of land, or alternatively be sourced from other feedstocks, such as forest and agricultural residues and municipal solid waste, but such supplies are projected to be inadequate for meeting the full cellulosic biofuel standard.[38]

Conversion of land not in cropland to crops for biofuel production may increase water consumption and runoff of fertilizers, herbicides, and sediment.[43] The impacts of climate change, particularly in areas where water availability may decrease (see Ch. 2: Our Changing Climate, Ch. 3: Water, and Ch. 6: Agriculture), however, may make it increasingly difficult to raise crops in arid regions of the country. The use of crops that are better suited to arid conditions and are efficient in recycling nutrients, such as switchgrass for cellulosic ethanol, could lower the vulnerability of biofuel production to climate change.[44] Another potential source of biomass for biofuel production is microalgae, but the existing technologies are still not carbon neutral, nor commercially viable.[45]

Carbon Capture and Storage

Carbon capture and storage (CCS) technologies have the potential to capture 90% of CO_2 emissions from coal and natural gas combustion by industrial and electric sector facilities and thus allow continued use of low-cost fossil fuels in a carbon-constrained future.[46] CCS captures CO_2 post- or pre-fuel combustion and injects the CO_2 into geologic formations for long-term storage. In addition, combining CCS with bioenergy applications represents one of a few potential options for actually removing CO_2 from the atmosphere[47] because carbon that was recently in the atmosphere and accumulated by growing plants can be captured and stored.

CCS substantially increases the cost of building and operating a power plant, both through up-front costs and additional energy use during operation (referred to as “parasitic loads” or an energy penalty).[46] Substantial amounts of water are also used to separate CO_2 from emissions and to generate the required parasitic energy. With current technologies, CCS can increase water consumption 30% to 100%.[48] Gasification technologies, where coal or biomass are converted to gases and CO_2 is separated before combustion, reduce the energy penalty and water requirements, but currently at higher capital costs.[49] As with other technologies, technology and design choices for CCS need to be balanced with water requirements and water availability. Climate change will influence the former via effects on energy demand and the latter via precipitation changes. CCS facilities themselves have relatively modest land demands compared to some other generation options. However, bioenergy use with CCS would imply a much stronger land linkage.

CCS facilities for electric power plants are currently operating at pilot scale, and a commercial scale demonstration project is under construction.[50] Although the potential opportunities are large, many uncertainties remain, including cost, demonstration at scale, environmental impacts, and what constitutes a safe, long-term geologic repository for sequestering carbon dioxide.[51]

Key Message 3: Challenges to Reducing Vulnerabilities

Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is challenging, but can improve the identification and evaluation of options for reducing climate change impacts.

The complex nature of interactions among energy, water, and land systems, particularly in the context of climate change, does not lend itself to simple solutions. The energy, water, and land interactions themselves create vulnerabilities to competing resource demands. Climate change is an additional stressor. However, resource management decisions are often focused on just one of these sectors. Where the three sectors are tightly coupled, options for mitigating or adapting to climate change and consideration of the tradeoffs associated with technological or resource availability may be limited. The complex nature of water and energy systems are also highlighted in Chapter 3 (Water), which discusses water constraints in many areas of the U.S., and in Chapter 4 (Energy), where it is noted that there will be challenges across the nation for water quality to comply with thermal regulatory needs for energy production.

A changing climate, particularly in areas projected to be warmer and drier, is expected to lead to drought and stresses on water supply, affecting energy, water, and land sectors in the United States. As the Texas drought of 2011 and 2012 illustrates, impacts to a particular sector, such as energy production, generate consequences for the others, such as water resource availability. Similarly, new energy development and production will require careful consideration of land and water sector resources. As a result, vulnerability to climate change depends on energy, water, and land linkages and on climate risks across all sectors, and decision-making is complex.

Water Stress in the U.S.

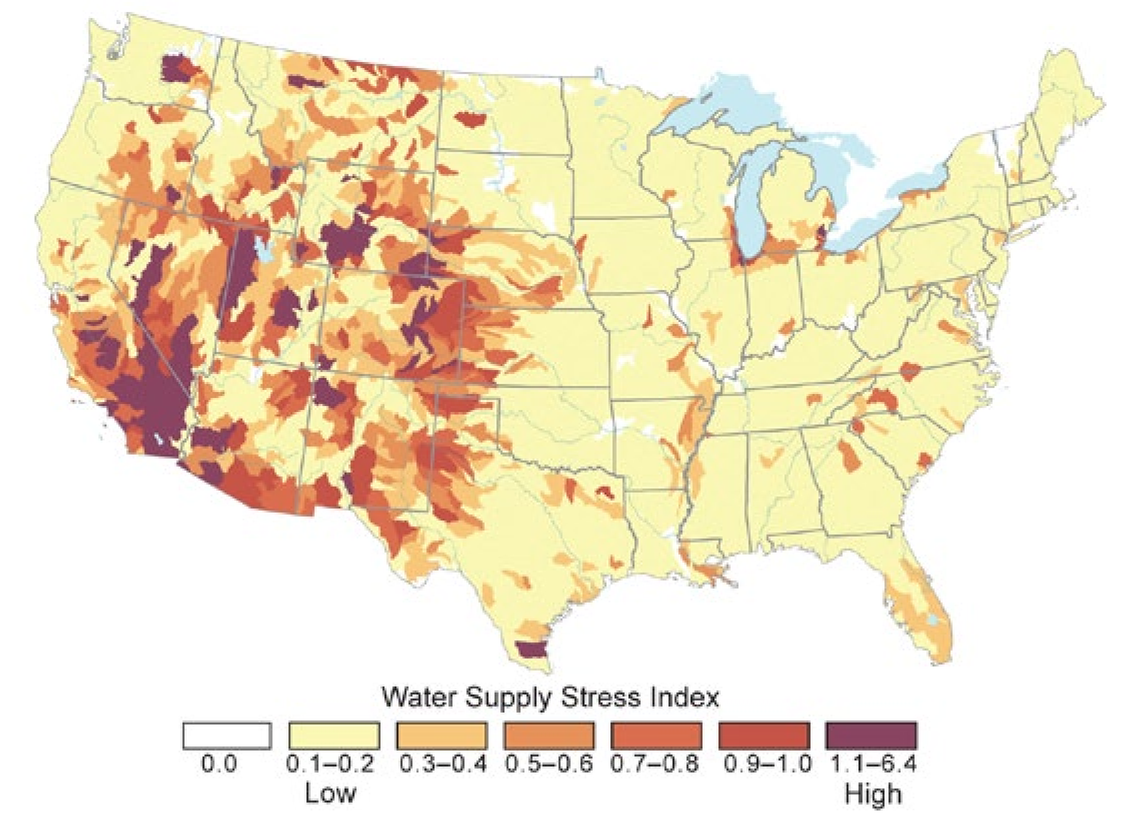

Figure 10.9. In many parts of the country, competing demands for water create stress in local and regional watersheds. Map shows a "water supply stress index" for the U.S. based on observations, with widespread stress in much of the Southwest, western Great Plains, and parts of the Northwest. Watersheds are considered stressed when water demand (from power plants, agriculture, and municipalities) exceeds 40% (water supply stress index of 0.4) of available supply. (Figure source: Averyt et al. 2011[20]).

The Columbia River Basin Land Use and Land Cover

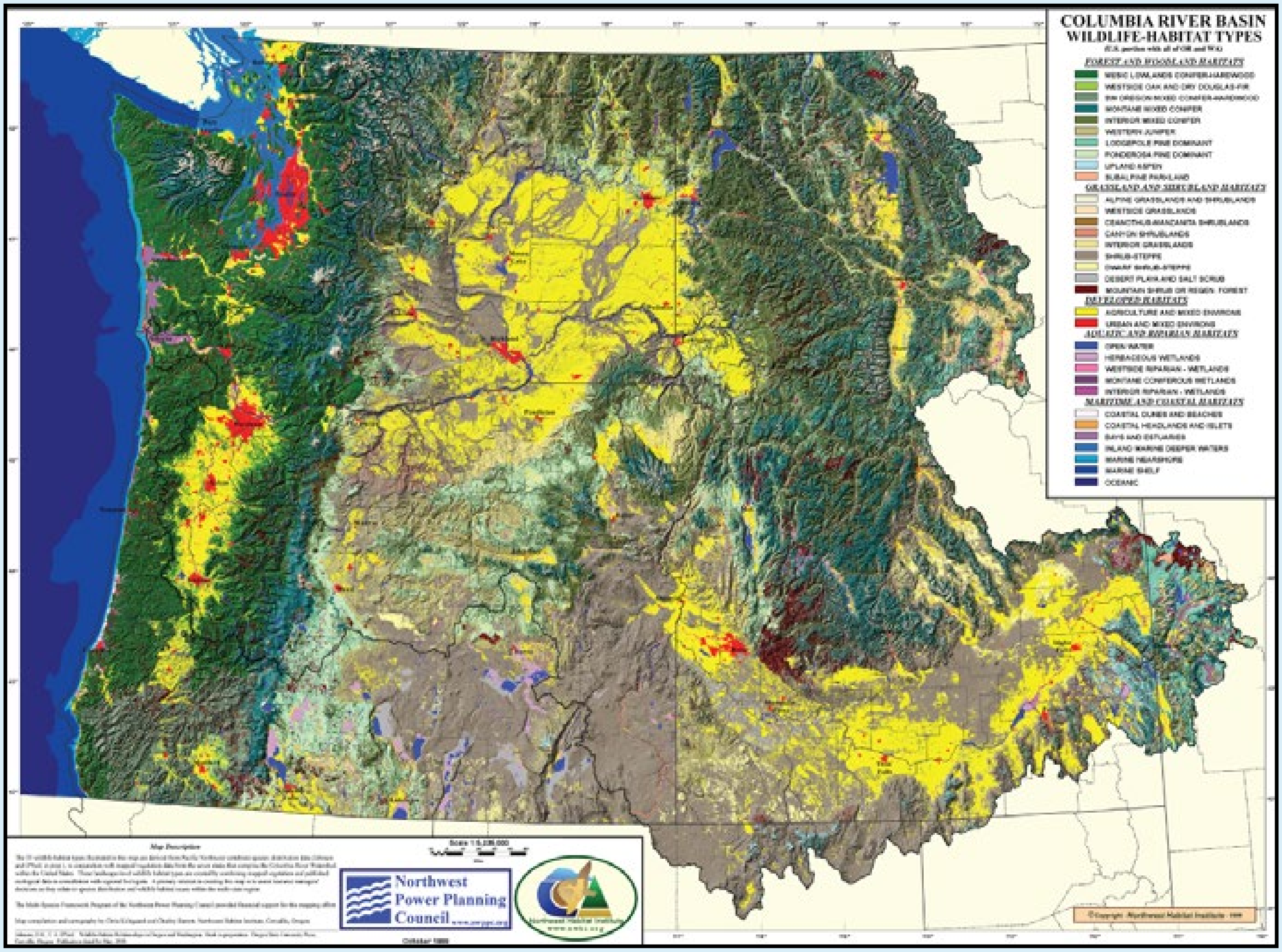

Figure 10.10. Agriculture is in yellow, forests are shades of green, shrublands are gray, and urban areas are in red. The river is used for hydropower generation, flood control, agriculture irrigation, recreation, support of forest and shrubland ecosystems, and fish and wildlife habitat. Climate change may impact the timing and supply of the water resources, affecting the multiple uses of this river system. (Figure source: Northwest Habitat Institute 1999).

The Columbia River Basin is one example of an area where risks, vulnerabilities, and opportunities are being jointly considered by a wide range of stakeholders and decision-makers (see Ch. 28: Adaptation). The Columbia River, which crosses the U.S.-Canada border, is the fourth largest river on the continent by volume, and it drives the production of more electricity than any other river in North America. Approximately 15% of the Columbia River Basin lies within British Columbia (Figure 10.10), but an average of 30% of the total average discharge originates from the Canadian portion of the watershed.[52] To provide flood control for the U.S. and predicted releases for hydropower generation, the Columbia River system is managed through a treaty that established a cooperative agreement between the United States and Canada to regulate the river for these two uses.[53] The basin also supports a range of other uses, such as navigation, tribal uses, irrigation, fish and wildlife habitat, recreation, and water resources for agricultural, industrial, and individual use. For all multi-use river basins, understanding the combined vulnerability of energy, water, and land use to climate change is essential to planning for water management and climate change adaptation.

A recent report projects a warmer annual, and drier summer, climate for the Northwest (Ch. 21: Northwest; Ch. 2: Our Changing Climate, Figures 2.14 and 2.15; Appendix 3: Climate Science Supplement, Figures 21 and 22),[54] potentially affecting both the timing and amounts of water availability. For example, if climate change reduces streamflow at certain times, fish and wildlife, as well as recreation, may be vulnerable.[55] Climate change stressors will also increase the vulnerability of the region's vast natural ecosystems and forests in multiple ways (see Ch. 7: Forests and Ch. 8: Ecosystems). Currently, only 30% of annual Columbia River Basin runoff can be stored in reservoirs.[56] Longer growing seasons might provide opportunities for greater agricultural production, but the projected warmer and drier summers could increase demand for water for irrigation, perhaps at the expense of other water uses due to storage limitations. Wetter winters might offset increased summer demands. However, the storage capacities of many water reservoirs with multiple purposes, including hydropower, were not designed to accommodate significant increases in winter precipitation. Regulations and operational requirements also constrain the ability to accommodate changing precipitation patterns (see Ch. 3: Water).

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Because of the complexity of interactions among energy, water, and land systems, considering the complete picture of climate impacts and potential adaptations can help provide better solutions. Adaptation to climate change occurs in large part locally or regionally, and conflicting stakeholder priorities, institutional commitments, and international agreements have the potential to complicate or even compromise adaption strategies with regard to energy, water, and land resources (see also Ch. 28: Adaptation). Effective adaptation to the impacts of climate change requires a better understanding of the interactions among the energy, water, and land resource sectors. Whether managing for water availability and quality in the context of energy systems, or land restrictions, or both, an improved dialog between the scientific and decision-making communities will be necessary to evaluate tradeoffs and compromises needed to manage and understand this complex system. This will require not only integrated and quantitative analyses of the processes that underlie the climate and natural systems, but also an understanding of decision criteria and risk analyses to communicate effectively with stakeholders and decision-makers.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

The authors met for a one-day face-to-face meeting, and held teleconferences approximately weekly from March through August 2012. They considered a variety of technical input documents, including a Technical Input Report prepared through an interagency process,[1] and 59 other reports submitted through the Federal Register Notice request for public input. The key messages were selected based on expert judgment, derived from the set of examples assembled to demonstrate the character and consequences of interactions among the energy, water, and land resource sectors.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Energy, water, and land systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate change vulnerability as well as adaptation and mitigation options for different regions of the country.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Technical Input Report (TIR): Climate and Energy-Water-Land System Interactions: Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment.[1] Technical input reports (59) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The TIR[1] incorporates the findings of a workshop, convened by the author team, of experts and stakeholders. The TIR summarizes numerous examples of interactions between specific sectors, such as energy and water or water and land use. A synthesis of these examples provides insight into how climate change impacts the interactions between these sectors.

The TIR[1] shows that the character and significance of interactions among the energy, water, and land resource sectors vary regionally. Additionally, the influence of impacts on one sector for the other sectors will depend on the specific impacts involved. Climate change impacts will affect the interactions among sectors, but this may not occur in all circumstances.

The key message is supported by the National Climate Assessment Climate Scenarios (for example, Kunkel et al. 2013[54]). Many of the historic trends included in the Climate Scenarios are based on data assembled by the Cooperative Observer Network of the National Weather Service (http://www.nws.noaa.gov/om/coop/). Regional climate outlooks are based on the appropriate regional chapter.

The Texas drought of 2011 and 2012 provides a clear example of cascading impacts through interactions among the energy, water, and land resource sectors.[3,4,5,7,8,9] The U.S. Drought Monitor (http://droughtmonitor.unl.edu/) provides relevant historical data. Evidence also includes articles appearing in the public press[11] and Internet media.[6]

New information and remaining uncertainties

The Texas drought of 2011 and 2012 demonstrates the occurrence of cascading impacts involving the energy, land, and water sectors; however, the Texas example cannot be generalized to all parts of the country or to all impacts of climate change (for example, see Chapter 3 for flooding and energy system impacts). The Technical Input Report[1] provides numerous additional examples and a general description of interactions that underlie cascading impacts between these resource sectors.

There are no major uncertainties regarding this key message. There are major uncertainties, however, in the magnitude of impacts in how decisions in one sector might affect another. The intensity of interactions will be difficult to assess under climate change.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high**. The primary limitation on the confidence assigned to this key message is with respect to its generality. The degree of interactions among the energy, water, and land sectors varies regionally as does the character and intensity of climate change.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

The dependence of energy systems on land and water supplies will influence the development of these systems and options for reducing greenhouse gas emissions, as well as their climate change vulnerability.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Technical Input Report (TIR): Climate and Energy-Water-Land System Interactions: Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment.[1] Technical input reports (59) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Synthesis and Assessment Product 2.1 of the Climate Change Science Program,[22] which informed the prior National Climate Assessment,[57] describes relationships among different future mixtures of energy sources, and associated radiative forcing of climate change, as a context for evaluating emissions mitigation options.

Energy, water, and land linkages represent constraints, risks, and opportunities for private/public planning and investment decisions. There are evolving water and land requirements for four energy technologies: natural gas from shale,[13] solar power,[34] biofuels,[38,39] and carbon dioxide capture and storage (CCS).[47] Each of these four technologies could contribute to reducing U.S. emissions of greenhouse gases. These technologies illustrate energy, water, and land linkages and other complexities for the design, planning, and deployment of our energy future.

Evidence for energy production and use are derived from U.S. government reports.[58] The contributions of hydraulic fracturing to natural gas production are based on a brief article by the Energy Information Administration[13] and a primer by the U.S. Department of Energy.[28] Information about water and energy demands for utility-scale solar power facilities is derived from two major DOE reports.[34,59] Distribution of U.S. solar energy resources is from Web-based products of the National Renewable Energy Laboratory (http://www.nrel.gov/gis/). On biofuels, there are government data on the scale of biomass-based energy,[13] and studies on water and land requirements and other social and environmental aspects.[38,39]

New information and remaining uncertainties

There are no major uncertainties regarding this key message. Progress in development and deployment of the energy technologies described has tended to follow a pattern: potential constraints arise because of dependence on water and land resources, but then these constraints motivate advances in technology to reduced dependence or result in adjustments of societal priorities. There are uncertainties in how energy systems' dependence on water will be limited by other resources, such as land; uncertainties about the effects on emissions and the development and deployment of future energy technologies; and uncertainties about the impacts of climate change on energy systems.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high**. The primary limitation on confidence assigned to this key message is with respect to its generality and dependence on technological advances. Energy technology development has the potential to reduce water and land requirements, and to reduce vulnerability to climate change impacts. It is difficult to forecast success in this regard for technologies such as CCS that are still in early phases of development.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is challenging, but can improve the identification and evaluation of options for reducing climate change impacts.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Technical Input Report (TIR): Climate and Energy-Water-Land System Interactions: Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment.[1] Technical input reports (59) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

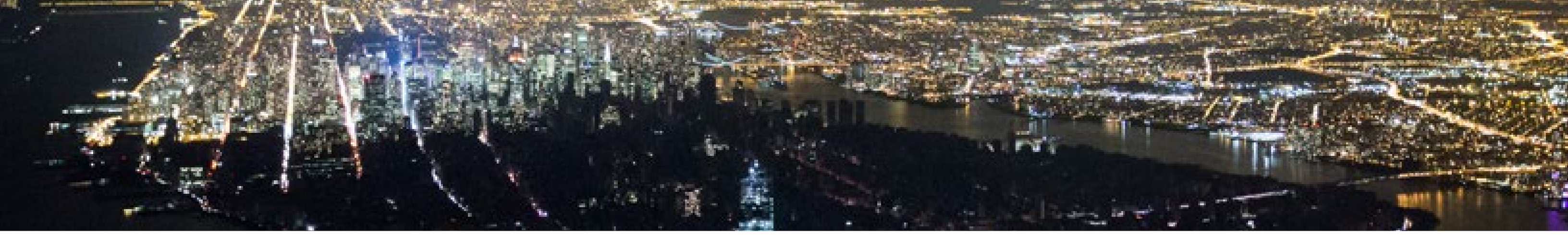
Interactions among energy, water, and land resource sectors can lead to stakeholder concerns that shape options for reducing vulnerability and thus for adapting to climate change. The Columbia River System provides a good example of an area where risks, vulnerabilities, and opportunities are being jointly considered.[55,56] The 2011 Mississippi basin flooding, which shut down substations, provides another example of the interactions of energy, water, and land systems (Ch. 3: Water). For all multi-use river basins, understanding the combined vulnerability of energy, water, and land use to climate change is essential to planning for water management and climate change adaptation.

New information and remaining uncertainties

There are no major uncertainties regarding this key message; however, it is highly uncertain the extent to which local, state and national policies will impact options to reduce vulnerability to climate change.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high**. The primary limitation on confidence assigned to this key message is with respect to the explicit knowledge of the unique characteristics of each region with regards to impacts of climate change on energy, water, land, and the interactions among these sectors.



Climate Change Impacts in the United States

CHAPTER 11
URBAN SYSTEMS, INFRASTRUCTURE, AND VULNERABILITY

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11 URBAN SYSTEMS, INFRASTRUCTURE, AND VULNERABILITY

KEY MESSAGES

1. **Climate change and its impacts threaten the well-being of urban residents in all U.S. regions. Essential infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts. The nation's economy, security, and culture all depend on the resilience of urban infrastructure systems.**
2. **In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.**
3. **Climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.**
4. **City government agencies and organizations have started adaptation plans that focus on infrastructure systems and public health. To be successful, these adaptation efforts require cooperative private sector and governmental activities, but institutions face many barriers to implementing coordinated efforts.**

Climate change poses a series of interrelated challenges to the country's most densely populated places: its cities. The United States is highly urbanized, with about 80% of its population living in cities and metropolitan areas. Many cities depend on infrastructure, like water and sewage systems, roads, bridges, and power plants, that is aging and in need of repair or replacement. Rising sea levels, storm surges, heat waves, and extreme weather events will compound these issues, stressing or even overwhelming these essential services.


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Heavy snowfalls during winter storms affect transportation systems and other urban infrastructure.

Cities have become early responders to climate change challenges and opportunities due to two simple facts: first, urban areas have large and growing populations that are vulnerable for many reasons to climate variability and change; and second, cities depend on extensive infrastructure systems and the resources that support them. These systems are often connected to rural locations at great distances from urban centers.

The term infrastructure is used broadly and includes systems and assets that are essential for national and economic security, national public health or safety, or to the overall well-being of residents. These include energy, water and wastewater, transportation, public health, banking and finance, telecommunications, food and agriculture, and information technology, among others.

Urban dwellers are particularly vulnerable to disruptions in essential infrastructure services, in part because many of these infrastructure systems are reliant on each other. For example, electricity is essential to multiple systems, and a failure in the electrical grid can affect water treatment, transportation services, and public health. These infrastructure systems – lifelines to millions – will continue to be affected by various climate-related events and processes.

As climate change impacts increase, climate-related events will have large consequences for significant numbers of people living in cities or suburbs. Also at risk from climate change are historic properties and sites as well as cultural resources and archeological sites. Vulnerability assessments and adaptation planning efforts could also include these irreplaceable resources. Changing conditions also create opportunities and challenges for urban climate adaptation (Ch. 28: Adaptation), and many cities have begun planning to address these changes.

Key Message 1: Urbanization and Infrastructure Systems

Climate change and its impacts threaten the well-being of urban residents in all U.S. regions. Essential infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts. The nation's economy, security, and culture all depend on the resilience of urban infrastructure systems.

Direct and interacting effects of climate change will expose people who live in cities across the United States to multiple threats. Climate changes affect the built, natural, and social infrastructure of cities, from storm drains to urban waterways to the capacity of emergency responders. Climate change increases the risk, frequency, and intensity of certain extreme events like intense heat waves, heavy downpours, flooding from intense precipitation and coastal storm surges, and disease incidence related to temperature and precipitation changes. The vulnerability of urban dwellers multiplies when the effects of climate change interact with pre-existing urban stressors, such as deteriorating infrastructure, areas of intense poverty, and high population density.

Three fundamental conditions define the key connections among urban systems, residents, and infrastructure.[1,2] First, cities are dynamic, and are constantly being built and rebuilt through cycles of investment and innovation. Second, infrastructure in many cities has exceeded its design life and continues to age, resulting in an increasingly fragile system. At both local and national levels, infrastructure requires ongoing maintenance and investment to avoid a decline in service. Third, urban areas present tremendous social challenges, given widely divergent socioeconomic conditions and dynamic residence patterns that vary in different parts of each city. Heightened vulnerability of coastal cities and other metropolitan areas that are subject to storm surge, flooding, and other extreme weather or climate events will exacerbate impacts on populations and infrastructure systems.

Approximately 245 million people live in U.S. urban areas, a number expected to grow to 364 million by 2050.[3] Paradoxically, as the economy and population of urban areas grew in past decades, the built infrastructure within cities and connected to cities deteriorated, becoming increasingly fragile and deficient.[1,2] Existing built infrastructure (such as buildings, energy, transportation, water, and sanitation systems) is expected to become more stressed in the next decades – especially when the impacts of climate change are added to the equation.[4] As infrastructure is highly interdependent, failure in particular sectors is expected to have cascading effects on most aspects of affected urban economies. Further expansion of the U.S. urban landscape into suburban and exurban spaces is expected, and new climate adaptation and resiliency plans will need to account for this (Ch. 28: Adaptation).[5] Significant increases in the costs of infrastructure investments also are expected as population density becomes more diffuse.[6]

The vulnerability of different urban populations to hazards and risks associated with climate change depends on three characteristics: their exposure to particular stressors, their sensitivity to impacts, and their ability to adapt to changing conditions.[8,9] Many major U.S. metropolitan areas, for example, are located on or near the coast and face higher exposure to particular climate impacts like sea level rise and storm surge, and thus may face complex and costly adaptation demands (Ch. 25: Coasts; Ch. 28: Adaptation). But as people begin to respond to new


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Coastal cities are vulnerable to sea level rise, storm surge, and related impacts.

Blackout in New York and New Jersey after Hurricane Sandy

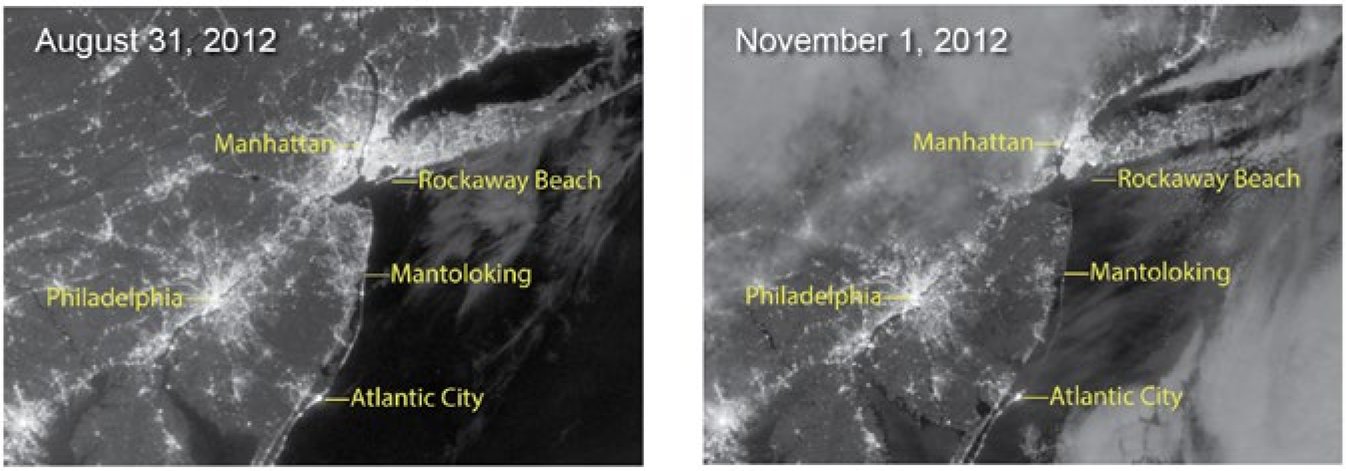

Figure 11.1. Extreme weather events can affect multiple systems that provide services for millions of people in urban settings. The satellite images depict city lights on a normal night (left) and immediately following Hurricane Sandy (right). Approximately five million customers in the New York metropolitan region lost power. (Figure source: NASA Earth Observatory[7]).

information about climate change through the urban development process, social and infrastructure vulnerabilities can be altered.[10] For example, the City of New York conducted a comprehensive review of select building and construction codes and standards in response to increased climate change risk in order to identify adjustments that could be made to increase climate resilience. Climate change stressors will bundle with other socioeconomic and engineering stressors already connected to urban and infrastructure systems.[1]

Key Message 2: Essential Services are Interdependent

In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.

Urban areas rely on links to multiple jurisdictions through a complex set of infrastructure systems.[11] For example, cities depend on other areas for supplies of food, materials, water, energy, and other inputs, and surrounding areas are destinations for products, services, and wastes from cities. If infrastructure and other connections among source areas and cities are disrupted by climate change, then the dependent urban area also will be affected.[12] Moreover, the economic base of an urban area depends on regional comparative advantage; therefore, if competitors, markets, and/or trade flows are affected by climate change, a particular urban area is also affected.[2]

Urban vulnerabilities to climate change impacts are directly related to clusters of supporting resources and infrastructures located in other regions. For example, about half of the nation's oil refineries are located in only four states.[13] Experience over the past decade with major infrastructure disruptions, such as the 2011 San Diego blackout, the 2003 Northeast blackout, and Hurricane Irene in 2011, has shown that the greatest losses from disruptive events may be distant from where damages started.[2] In another example, Hurricane


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A failure of the electrical grid can affect everything from water treatment to public health.

Katrina disrupted oil terminal operations in southern Louisiana, not because of direct damage to port facilities, but because workers could not reach work locations through surface transportation routes and could not be housed locally because of disruption to potable water supplies, housing, and food shipments.[14]

Although infrastructures and urban systems are often considered individually – for example, transportation or water supply or wastewater/drainage – they are usually highly interactive and interdependent.[15]

Urban Support Systems are Interconnected

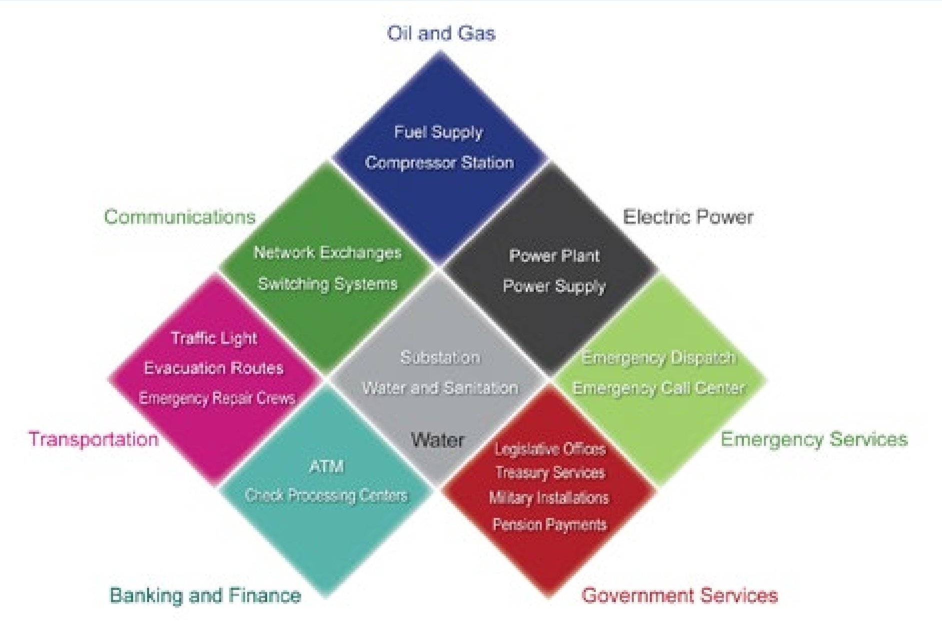

Figure 11.2. In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other systems. When power supplies that serve urban areas are interrupted after a major weather event, for example, public health, transportation, and banking systems may all be affected. This schematic drawing illustrates some of these connections. (Figure source: adapted from Wilbanks et al. 2012[2]).

Such interdependencies can lead to cascading disruptions throughout urban infrastructures. These disruptions, in turn, can result in unexpected impacts on communication, water, and public health sectors, at least in the short term. On August 8, 2007, New York City experienced an intense rainfall and thunderstorm event during the morning commute, where between 1.4 and 3.5 inches of rain fell within two hours.[16] The event started a cascade of transit system failures – eventually stranding 2.5 million riders, shutting down much of the subway system, and severely disrupting the city's bus system.[16,17] The storm's impact was unprecedented and, coupled with two other major system disruptions that occurred in 2004 and 2007, became the impetus for a full-scale assessment and review of transit procedures and policy in response to climate change.[16,17,18]

In August 2003, an electric power blackout that caused 50 million people in the U.S. Northeast and Midwest and Ontario, Canada, to lose electric power further illustrates the interdependencies of major infrastructure systems. The blackout caused significant indirect damage, such as shutdowns of water treatment plants and pumping stations. Other impacts included interruptions in communication systems for air travel and control systems for oil refineries. At a more local level, the lack of air conditioning and elevator access meant many urban residents were stranded in over-heating high-rise apartments. Similar cascading impacts have been observed from extreme weather events such as Hurricanes Katrina and Irene.[2] In fact, as urban infrastructures become more interconnected and more complex, the likelihood of large-scale cascading impacts will increase as risks to infrastructure increase.[19]

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Storm surges reach farther inland as they ride on top of sea levels that are higher due to warming.

HURRICANE SANDY: URBAN SYSTEMS, INFRASTRUCTURE, AND VULNERABILITY


Courtesy of NOAA

Sandy made landfall on the New Jersey shore just south of Atlantic City on October 29, 2012, and became one of the most damaging storms to strike the continental United States. Sandy affected cities throughout the Atlantic seaboard, extending across the eastern United States to Chicago, Illinois, where it generated 20-foot waves on Lake Michigan and flooded the city's Lake Shore Drive. The storm's strength and resulting impact has been correlated with Atlantic Ocean water temperatures near the coast that were roughly 5°F above normal, and with sea level rise along the region's coastline as a result of a warming climate.

Sandy caused significant loss of life as well as tremendous destruction of property and critical infrastructure. It disrupted daily life for millions of coastal zone residents across the New York-New Jersey metropolitan area, despite this being one of the best disaster-prepared coastal regions in the country. The death toll from Sandy in the metropolitan region exceeded 100, and the damage was estimated to be at least $65 billion.[20,21] At its peak, the storm cut electrical power to more than 8.5 million customers.[21]

The death and injury, physical devastation, multi-day power, heat, and water outages, gasoline shortages, and cascade of problems from Sandy's impact reveal what happens when the complex, integrated systems upon which urban life depends are stressed and fail. One example is what occurred after a Consolidated Edison electricity distribution substation in lower Manhattan ceased operation at approximately 9 PM Monday evening, when its flood protection barrier (designed to be 1.5 feet above the 10-foot storm surge of record) was overtopped by Sandy's 14-foot storm surge. As the substation stopped functioning, it immediately caused a system-wide loss of power for more than 200,000 customers. Residents in numerous high-rise apartment buildings were left without heat and lights, and also without elevator service and water (which must be pumped to upper floors).

Sandy also highlighted the vast differences in vulnerabilities across the extended metropolitan region. Communities and neighborhoods on the coast were most vulnerable to the physical impact of the record storm surge. Many low- to moderate-income residents live in these areas and suffered damage to or loss of their homes, leaving tens of thousands of people displaced or homeless. As a specific sub-population, the elderly and infirm were highly vulnerable, especially those living in the coastal evacuation zone and those on upper floors of apartment buildings left without elevator service. These individuals had limited adaptive capacity because they could not easily leave their residences.

Even with the extensive devastation, the effects of the storm would have been far worse if local climate resilience strategies had not been in place. For example, the City of New York and the Metropolitan Transportation Authority worked aggressively to protect life and property by stopping the operation of the city's subway before the storm hit and moving the train cars out of low-lying, flood-prone areas. At the height of the storm surge, all seven of the city's East River subway tunnels flooded. Catastrophic loss of life would have resulted if there had been subway trains operating in the tunnels when the storm struck. The storm also fostered vigorous debate among local and state politicians, other decision-makers, and stakeholders about how best to prepare the region for future storms. Planning is especially important given the expectation of increases in flood frequency resulting from more numerous extreme precipitation events and riverine and street level flooding, and coastal storm surge flooding associated with accelerated sea level rise and more intense (yet not necessarily more numerous) tropical storms.

Key Message 3: Social Vulnerability and Human Well-Being

Climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.

"Social vulnerability" describes characteristics of populations that influence their capacity to prepare for, respond to, and recover from hazards and disasters.[22,23,24] Social vulnerability also refers to the sensitivity of a population to climate change impacts and how different people or groups are more or less vulnerable to those impacts.[25] Those characteristics that most often influence differential impacts include socioeconomic status (wealth or poverty), age, gender, special needs, race, and ethnicity.[26] Further, inequalities reflecting differences in gender, age, wealth, class, ethnicity, health, and disabilities also influence coping and adaptive capacity, especially to climate change and climate-sensitive hazards.[27]

The urban elderly are particularly sensitive to heat waves. They are often physically frail, have limited financial resources, and live in relative isolation in their apartments. They may not have adequate cooling (or heating), or may be unable to temporarily relocate to cooling stations. This combination led to a significant number of elderly deaths during the 1995 Chicago heat wave.[28] Similarly, the impacts of Hurricane Katrina in New Orleans illustrated profound differences based on race, gender, and class where these social inequalities strongly influenced the capacity of residents to prepare for and respond to the events.[29] It is difficult to assess the specific nature of vulnerability for particular groups of people. Urban areas are not homogeneous in terms of the social structures that influence inequalities. Also, the nature of the vulnerability is context specific, with both temporal and geographic determinants, and these also vary between and within urban areas.

Key Message 4: Trends in Urban Adaptation – Lessons from Current Adopters

City government agencies and organizations have started adaptation plans that focus on infrastructure systems and public health. To be successful, these adaptation efforts require cooperative private sector and governmental activities, but institutions face many barriers to implementing coordinated efforts.

City preparation efforts for climate change include planning for ways in which the infrastructure systems and buildings, ecosystem and municipal services, and residents will be affected. In the first large-scale analysis of U.S. cities, a 2011 survey showed that 58% of respondents are moving forward on climate adaptation (Ch. 28: Adaptation), defined as any activity to address impacts that climate change could have on a community. Cities are engaged in activities ranging from education and outreach to assessment, planning, and implementation, with 48% reporting that they are in the preliminary planning and discussion phases.[30]

Cities either develop separate strategic adaptation plans[30,32] or integrate adaptation into community or general plans (as have Seattle, Washington; Portland, Oregon; Berkeley, California; and Homer, Alaska) (Ch. 28: Adaptation).[1] Some climate action plans target certain sectors like critical infrastructure,[24,33] and these have been effective in diverse contexts ranging from hazard mitigation and public-health planning to coastal-zone management and economic development.

Cities have employed several strategies for managing adaptation efforts. For example, some approaches to climate adaptation planning require both intra- and inter-governmental agency and department coordination ("New York City Climate Action") (Ch. 28: Adaptation). As a result, many cities focus on sharing information and examining what aspects of government operations will be affected by climate change impacts in order to gain support from municipal agency stakeholders and other local officials.[34] Some cities also have shared climate change action experiences, both within the United States and internationally, as is the case with ongoing communication between decision-makers in New York City and London, England.

National, state, and local policies play an important role in fostering and sustaining adaptation. There are no national regulations specifically designed to promote urban adaptation. However, existing federal policies, like the National Historic Preservation Act and National Environmental Policy Act – particularly through its impact assessment provision and evaluation criteria process – can provide incentives for adaptation strategies for managing federal property in urban areas.[1,35] In addition, recent activities of federal agencies focused on promoting adaptation and resilience have been developed in partnership with cities like Miami and New York.[36] Policies and planning measures at the local level, such as building codes, zoning regulations, land-use plans, water supply management, green infrastructure initiatives, health care planning, and disaster mitigation efforts, can support adaptation.[1,2,37]

Engaging the public in adaptation planning and implementation has helped to inform and educate the community at large

New York City and Sea Level Rise

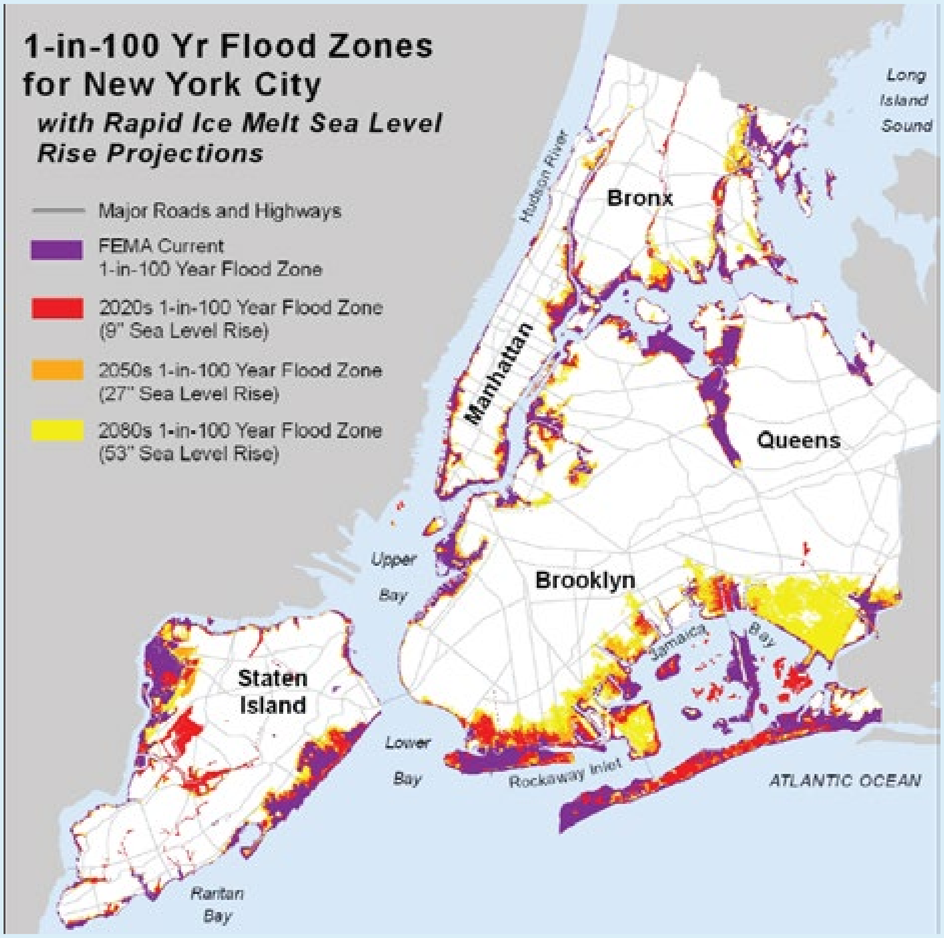

Figure 11.3. Map shows areas in New York's five boroughs that are projected to face increased flooding over the next 70 years, assuming an increased rate of sea level rise from the past century's average. As sea level rises, storm surges reach farther inland. Map does not represent precise flood boundaries, but illustrates projected increases in areas flooded under various sea level rise scenarios. (Figure source: New York City Panel on Climate Change 2013[31]).

about climate change, while ensuring that information and ideas flow back to policymakers.[38] Engagement can also help in identifying vulnerable populations[39] and in mobilizing people to encourage policy changes and take individual actions to reduce and adapt to climate change.[40] For instance, the Cambridge Climate Emergency Congress selected a demographically diverse group of resident delegates and engaged them in a deliberative process intended to express preferences and generate recommendations to inform climate action.[41] In addition, the Boston Climate Action Leadership Committee was initiated by the Mayor's office with the expectation that they would rely on public consultation to develop recommendations for updating the city's climate action plan.[42]

There are many barriers to action at the city level. Proactive adaptation efforts require that anticipated climate changes and impacts are evaluated and addressed in the course of the planning process (Ch. 26: Decision Support; Ch. 28: Adaptation).[43] This means that climate projections and impact assessment data must be available, but most U.S. cities are unable to access suitable data or perform desired analyses.[36] To address technical aspects of adaptation, cities are promoting cooperation with local experts, such as the New York City Panel on Climate Change, which brings together experts from academia and the public and private sectors to consider how the region's critical infrastructure will be affected by, and can be protected from, future climate change.[10,44] A further illustration comes from Chicago, where multi-departmental groups are focusing on specific areas identified in Chicago's Climate Action Plan.[45]

Private sector involvement can be influential in promoting city-level adaptation (Ch. 28: Adaptation). Many utilities, for example, have asset management programs that address risk and vulnerabilities, which could also serve to address climate change. Yet to date there are limited examples of private sector interests working cooperatively with governments to limit risk. Instances where cooperation has taken place include property insurance companies[1,46] and engineering firms that provide consulting services to cities. For example, firms providing infrastructure system plans have begun to account for projected changes in precipitation in their projects.[47] With city and regional infrastructure systems, recent attention has focused on the potential role of private sector-generated smart technologies to improve early warning of extreme precipitation and heat waves, as well as establishing information systems that can inform local decision-makers about the status and efficiency of infrastructure.[46,48]

Uncertainty, in both the climate system and modeling techniques, is often viewed as a barrier to adaptation action (Ch. 28: Adaptation).[49] Urban and infrastructure managers, however, recognize that understanding of sources and magnitude of future uncertainty will continue to be refined,[39] and that an incremental and flexible approach to planning that draws on both structural and nonstructural measures is prudent.[44,46,50] Gaining the commitment and support of local elected officials for adaptation planning and implementation is another important challenge.[30] A compounding problem is that cities and city administrators face a wide range of other stressors demanding their attention, and have limited financial resources (see "Advancing Climate Adaptation in a Metropolitan Region").[46]

Integrating climate change action in everyday city and infrastructure operations and governance (referred to as "mainstreaming") is an important planning and implementation tool for advancing adaptation in cities (Ch. 28: Adaptation).[44,46] By integrating climate change considerations into daily operations, these efforts can forestall the need to develop a new and isolated set of climate change-specific policies or procedures.[39] This strategy enables cities and other government agencies to take advantage of existing funding sources and programs, and achieve co-benefits in areas such as sustainability, public health, economic development, disaster preparedness, and environmental justice. Pursuing low-cost, no-regrets options is a particularly attractive short-term strategy for many cities.[39,46]

Over the long term, responses to severe climate change impacts, such as sea level rise and greater frequency and intensity of other climate-related hazards, are of a scale and complexity that will likely require major expenditures and structural changes,[1,46] especially in urban areas. When major infrastructure decisions must be made in order to protect human lives and urban assets, cities need access to the best available science, decision support tools, funding, and guidance. The Federal Government is seen by local officials to have an important role here by providing adaptation leadership and financial and technical resources, and by conducting and disseminating research (Ch. 28: Adaptation).[36,39,46]

ADVANCING CLIMATE ADAPTATION IN A METROPOLITAN REGION

Coordinating efforts across many jurisdictional boundaries is a major challenge for adaptation planning and practice in extended metropolitan regions and associated regional systems (Ch. 28: Adaptation). Regional government institutions may be well suited to address this challenge, as they cover a larger geographic scope than individual cities, and have potential to coordinate the efforts of multiple jurisdictions.[1] California already requires metropolitan planning organizations to prepare Sustainable Communities Strategies (SCS) as part of the Regional Transportation Plan process.[51] While its focus is on reducing emissions, SCS plans prepared to date have also introduced topics related to climate change impacts and adaptation.[52] Examples of climate change vulnerabilities that could benefit from a regional perspective include water shortages, transportation infrastructure maintenance, loss of native plant and animal species, and energy demand.

NEW YORK CITY CLIMATE ACTION

New York City leaders recognized that climate change represents a serious threat to critical infrastructure and responded with a comprehensive program to address climate change impacts and increase resilience.[1,2] The 2010 "Climate Change Adaptation in New York City: Building a Risk Management Response" report was prepared by the New York City Panel on Climate Change as a part of the city's long-term sustainability plan.[10] Major components of the process and program include:

- establishing multiple participatory processes to obtain broad public input, including a Climate Change Adaptation Task Force that included private and public stakeholders;[46]
- forming an expert technical advisory body, the New York City Panel on Climate Change (NPCC), to support the Task Force;
- developing a Climate Change Assessment and Action Plan that helps improve responses to present-day climate variability as well as projected future conditions;
- defining "Climate Protection Levels" to address the effectiveness of current regulations and design standards to respond to climate change impacts; and
- producing adaptation assessment guidelines that recognize the need for flexibility to reassess and adjust strategies over time. The guidelines include a risk matrix and prioritization framework intended to become integral parts of ongoing risk management and agency operations.

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11: URBAN SYSTEMS, INFRASTRUCTURE, AND VULNERABILITY

SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

In developing key messages, the report author team engaged in multiple technical discussions via teleconference. A consensus process was used to determine the final set of key messages, which are supported by extensive evidence documented in two Technical Report Inputs to the National Climate Assessment on urban systems, infrastructure, and vulnerability: 1) *Climate Change and Infrastructure, Urban Systems, and Vulnerabilities: Technical Report for the U.S. Department of Energy in Support of the National Climate Assessment*,[2] and 2) *U.S. Cities and Climate Change: Urban, Infrastructure, and Vulnerability Issues*.[1] Other Technical Input reports (56) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Key message 1 Traceable Account

Climate change and its impacts threaten the well-being of urban residents in all U.S. regions. Essential infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts. The nation's economy, security, and culture all depend on the resilience of urban infrastructure systems.

Description of evidence base

Recent studies have reported that population and economic growth have made urban infrastructure more fragile and deficient,[1,2] with work projecting increased stresses due to climate change[4] and increased costs of adaptation plans due to more extensive urban development.[6] Additionally, a few publications have assessed the main drivers of vulnerability[8,9] and the effects of the amalgamation of climate change stresses with other urban and infrastructure stressors.[1]

New information and remaining uncertainties

Given that population trends and infrastructure assessments are well established and documented, the largest uncertainties are associated with the rate and extent of potential climate change.

Since the 2009 National Climate Assessment,[53] recent publications have explored the driving factors of vulnerability in urban systems[8,9] and the effects of the combined effect of climate change and existing urban stressors.[1]

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that climate change and its impacts threaten the well-being of urban residents in all regions of the U.S.

Given the evidence base and remaining uncertainties, confidence is **very high** that essential local and regional infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message 2 Traceable Account

In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.

Description of evidence base

The interconnections among urban systems and infrastructures have been noted in the past,[19] with recent work expanding on this principle to assess the risks this interconnectivity poses. One study[15] explored the misconception of independent systems, and stressed instead the interactive and interdependent nature of systems. The effects of climate change on one system ultimately affect systems that are dependent upon it.[12] One of the foundational Technical Input Reports examined the economic effects from climate change and how they will affect urban areas.[2] Noted examples of this interconnectivity can be found in a number of publications concerning Hurricane Katrina,[14] intense weather in New York City,[16,17] and the vulnerability of U.S. oil refineries and electric power plants.[2,13]

New information and remaining uncertainties

Recent work has delved deeper into the interconnectivity of urban systems and infrastructure,[2,12] and has expressed the importance of understanding these interactions when adapting to climate change.

The extensive number of infrastructure assessments has resulted in system interdependencies and cascade effects being well documented. Therefore, the most significant uncertainties are associated with the rate and extent of potential climate change.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that in urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems.

KEY MESSAGE 3 TRACEABLE ACCOUNT

Climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.

Description of evidence base

The topic of social vulnerability has been extensively studied,[22,23,24] with some work detailing the social characteristics that are the most influential.[26] More recent work has addressed the vulnerability of populations to climate change[25] and how social inequalities influence capacity to adapt to climate change.[27] Some empirical studies of U.S. urban areas were explored concerning these issues.[9]

New information and remaining uncertainties

Given that population trends and socioeconomic factors associated with vulnerability and adaptive capacity are well established and documented, the largest uncertainties are associated with the rate and extent of potential climate change.

Recent work has addressed the social vulnerabilities to climate change at a more detailed level than in the past,[23,25] providing information on the constraints that social vulnerabilities can have on climate change adaptation.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that the climate vulnerability and adaptive capacity of urban residents and communities are influenced by pronounced social inequalities that reflect age, ethnicity, gender, income, health, and (dis)ability differences.

KEY MESSAGE 4 TRACEABLE ACCOUNT

City government agencies and organizations have started adaptation plans that focus on infrastructure systems and public health. To be successful, these adaptation efforts require cooperative private sector and governmental activities, but institutions face many barriers to implementing coordinated efforts.

Description of evidence base

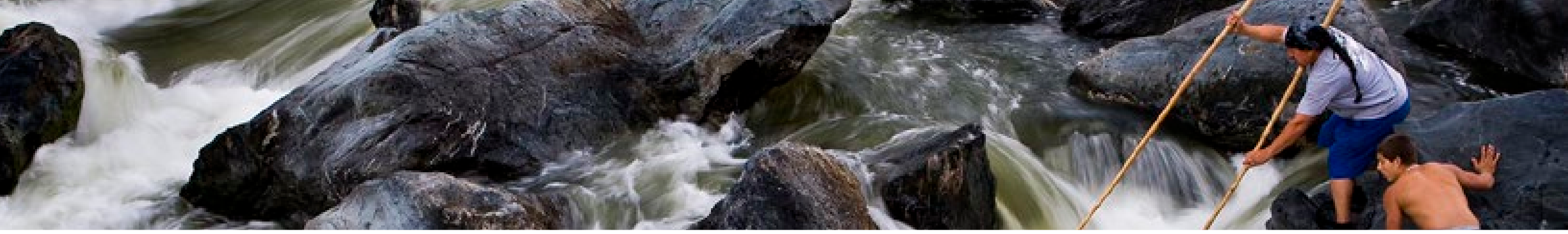
Urban adaptation is already underway with a number of cities developing plans at the city[30,32,33] and state levels,[30] with some integrating adaptation into community plans[1] and sharing information and assessing potential impacts.[34] Some recent publications have explored how incentives and administrative and financial support can benefit climate adaptation through policy planning at the local level[1,2,37] and by engaging the public.[38,39,40] Barriers exist that can hinder the adaptation process, which has been demonstrated through publications assessing the availability of scientific data[30,36] that is integral to the evaluation and planning process,[43] uncertainty in the climate system and modeling techniques,[49] and the challenges of gaining support and commitment from local officials.[30,46]

New information and remaining uncertainties

Besides uncertainties associated with the rate and extent of potential climate change, uncertainties emerge from the fact that, to date, there have been few extended case studies examining how U.S. cities are responding to climate change (<10 studies). Furthermore, only one large-scale survey of U.S. cites has been conducted for which results have been published and widely available.[30]

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **very high** that city government agencies and organizations have started urban adaptation efforts that focus on infrastructure systems and public health.



Climate Change Impacts in the United States

CHAPTER 12

INDIGENOUS PEOPLES, LAND, AND RESOURCES

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On the Web: http://nca2014.globalchange.gov/report/sectors/indigenous-peoples

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

12 INDIGENOUS PEOPLES, LAND, AND RESOURCES

Key Messages

1. **Observed and future impacts from climate change threaten Native Peoples' access to traditional foods such as fish, game, and wild and cultivated crops, which have provided sustenance as well as cultural, economic, medicinal, and community health for generations.**
2. **A significant decrease in water quality and quantity due to a variety of factors, including climate change, is affecting drinking water, food, and cultures. Native communities' vulnerabilities and limited capacity to adapt to water-related challenges are exacerbated by historical and contemporary government policies and poor socioeconomic conditions.**
3. **Declining sea ice in Alaska is causing significant impacts to Native communities, including increasingly risky travel and hunting conditions, damage and loss to settlements, food insecurity, and socioeconomic and health impacts from loss of cultures, traditional knowledge, and homelands.**
4. **Alaska Native communities are increasingly exposed to health and livelihood hazards from increasing temperatures and thawing permafrost, which are damaging critical infrastructure, adding to other stressors on traditional lifestyles.**
5. **Climate change related impacts are forcing relocation of tribal and indigenous communities, especially in coastal locations. These relocations, and the lack of governance mechanisms or funding to support them, are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.**

> *We humbly ask permission from all our relatives; our elders, our families, our children, the winged and the insects, the four-legged, the swimmers, and all the plant and animal nations, to speak. Our Mother has cried out to us. She is in pain. We are called to answer her cries. Msit No'Kmaq – All my relations!*
>
> — Indigenous Prayer

The peoples, lands, and resources of indigenous communities in the United States, including Alaska and the Pacific Rim, face an array of climate change impacts and vulnerabilities that threaten many Native communities. The consequences of observed and projected climate change have and will undermine indigenous ways of life that have persisted for thousands of years. Key vulnerabilities include the loss of traditional knowledge in the face of rapidly changing ecological conditions, increased food insecurity due to reduced availability of traditional foods, changing water availability, Arctic sea ice loss, permafrost thaw, and relocation from historic homelands.[1,2,3,4]

Climate change impacts on many of the 566 federally recognized tribes and other tribal and indigenous groups in the U.S. are projected to be especially severe, since these impacts are compounded by a number of persistent social and economic problems.[6,7] The adaptive responses to multiple social and ecological challenges arising from climate impacts on indigenous communities will occur against a complex backdrop of centuries-old cultures already stressed by historical events and contemporary conditions.[8] Individual tribal responses will be grounded in the particular cultural and environmental heritage of each community, their social and geographical history, spiritual values, traditional ecological knowledge, and worldview. Furthermore, these responses will be informed by each group's distinct political and legal status, which includes the legacy of more than two centuries of non-Native social and governmental institutional arrangements, relationships, policies, and practices. Response options will be informed by the often limited economic resources available to meet these challenges, as well as these cultures' deeply ingrained relationships with the natural world.[9,10,11,12]

The history and culture of many tribes and indigenous peoples are critical to understand before assessing additional climate change impacts. Most U.S. Native populations already face adverse socioeconomic factors such as extreme poverty; substandard and inadequate housing; a lack of health and community services, food, infrastructure, transportation, and education; low employment; and high fuel costs; as well as historical and current institutional and policy issues related to Native resources.[7,11,12,13] The overwhelming driver of these adverse social indicators is pervasive poverty on reservations and in Native communities, as illustrated by an overall 28.4% poverty rate (36% for families with children) on reservations, compared with 15.3% nationally.[13] Some reservations are far worse off, with more than 60% poverty rates and, in some cases, extremely low income levels (for example, Pine Ridge Reservation has the lowest per capita income in the U.S. at $1,535 per year).[14]

These poverty levels result in problems such as: a critical housing shortage of well over two hundred thousand safe, healthy, and affordable homes;[15] a homeless rate of more than 10% on reservations;[16] a lack of electricity (more than 14% of reservation homes are without power, ten times the national average, and, on the Navajo Reservation, about 40% of homes have no electricity[17]); lack of running water in one-fifth of all reservation homes and for about one-third of people on the Navajo Reservation (compared with 1% of U.S. national households);[18,19,20] and an almost complete lack of modern telecommunications – fewer than 50% of homes have phone service, fewer than 10% of residents have Internet access, and many reservations have no cell phone reception.[21] In addition, Native populations are also vulnerable because their physical, mental, intellectual, social, and cultural well-being is traditionally tied to a close relationship with the natural world, and because of their dependence on the land and resources for basic needs such as medicine, shelter, and food.[22,23] Climate changes will exacerbate many existing barriers to providing for these human needs, and in many cases will make adaptive responses more difficult.

Of the 5.2 million American Indians and Alaska Natives registered in the U.S. Census, approximately 1.1 million live on or near reservations or Native lands, located mostly in the Northwest, Southwest, Great Plains, and Alaska. Tribal lands include approximately 56 million acres (about 3% of U.S. lands) in the 48 contiguous states and 44 million acres (about 42% of Alaska's land base) held by Alaska Native corporations.[5] Most reservations are small and often remote or isolated, with a few larger exceptions such as the Navajo Reservation in Arizona, Utah, and New Mexico, which has 175,000 residents.[5]

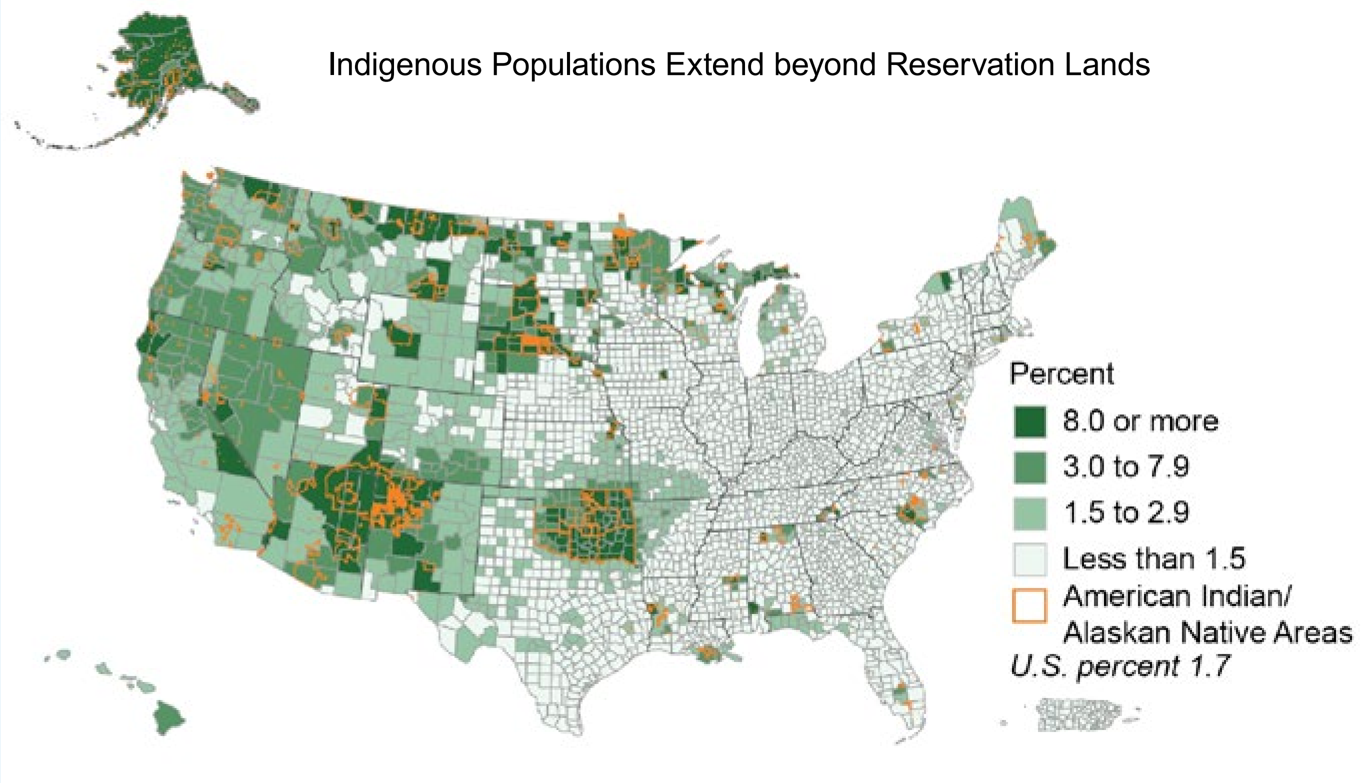
Indigenous Populations Extend beyond Reservation Lands

Figure 12.1. Census data show that American Indian and Alaska Native populations are concentrated around, but are not limited to, reservation lands like the Hopi and Navajo in Arizona and New Mexico, the Choctaw, Chickasaw, and Cherokee in Oklahoma, and various Sioux tribes in the Dakotas and Montana. Not depicted in this graphic is the proportion of Native Americans who live off-reservation and in and around urban centers (such as Chicago, Minneapolis, Denver, Albuquerque, and Los Angeles) yet still maintain strong family ties to their tribes, tribal lands, and cultural resources. (Figure source: Norriset al. 2012[5]).

House being built on Pine Ridge Reservation

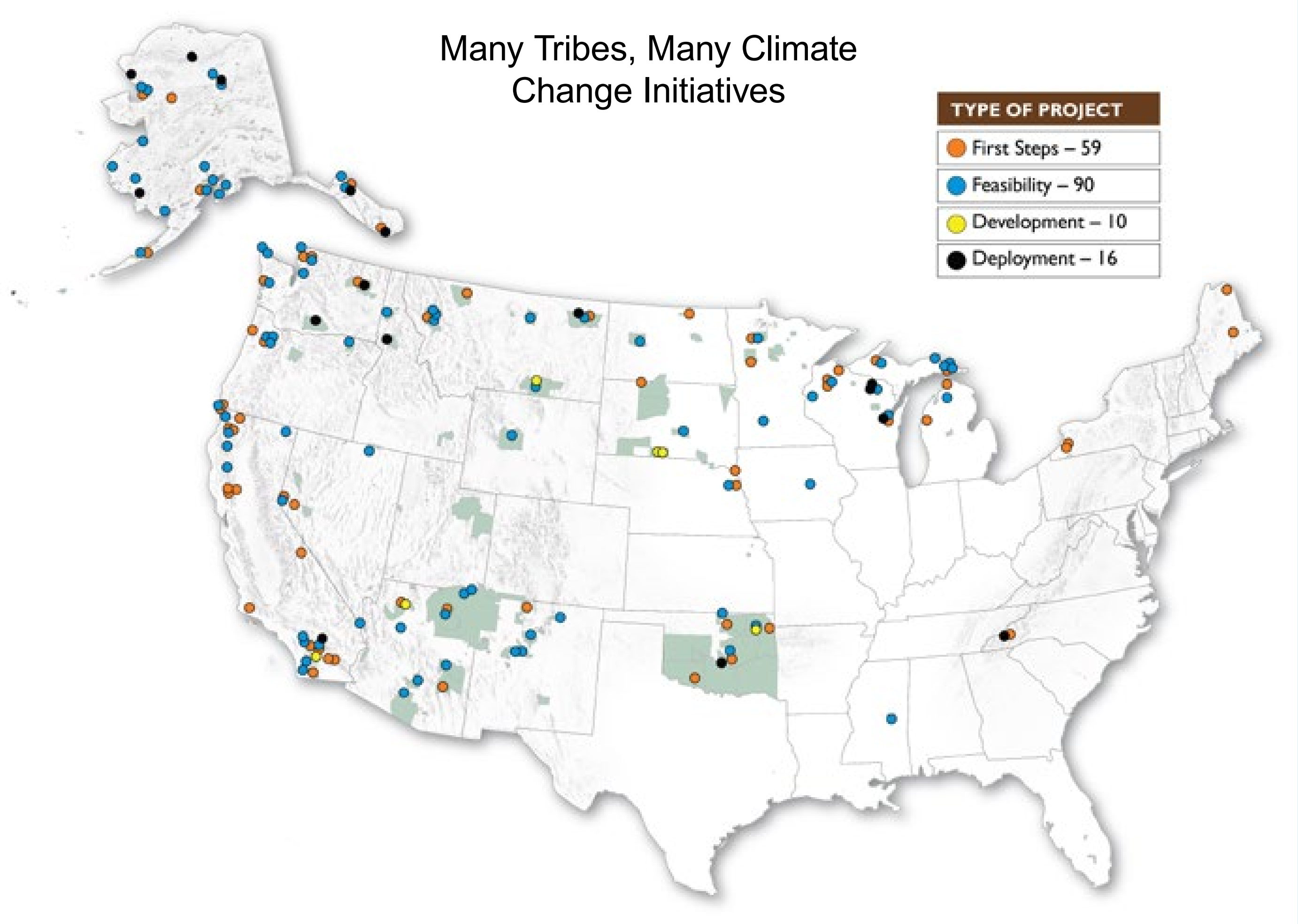

Figure 12.2. From developing biomass energy projects on the Quinault Indian Nation in Washington and tribal and intertribal wind projects in the Great Plains,[24] to energy efficiency improvement efforts on the Cherokee Indian Reservation in North Carolina and the sustainable community designs being pursued on the Lakota reservations in the Dakotas (see also Ch. 19: Great Plains),[25] tribes are investigating ways to reduce future climate changes. The map shows only those initiatives by federally recognized tribes that are funded through the Department of Energy. (Figure source: U.S. Department of Energy 2011[26]).

Native American, Alaska Native, and other indigenous communities across the U.S. share unique historical and cultural relationships with tribal or ancestral lands, significantly shaping their identities and adaptive opportunities.[11] Some climate change adaptation opportunities exist on Native lands, and traditional knowledge can enhance adaptation and sustainability strategies. In many cases, however, adaptation options are limited by poverty, lack of resources, or – for some Native communities, such as those along the northern coast of Alaska constrained by public lands or on certain low-lying Pacific Islands – because there may be no land left to call their own. Conversely, for these same reasons, Native communities – especially in the Arctic – are also increasingly working to identify new economic opportunities associated with climate change and development activities (for example, oil and gas, mining, shipping, and tourism) and to optimize employment opportunities.[1,27,28]

Climate Change and Traditional Knowledge

Indigenous traditional knowledge has emerged in national and international arenas as a source of rich information for indigenous and non-indigenous climate assessments, policies, and adaptation strategies. Working Group II of the Intergovernmental Panel on Climate Change Fourth Assessment Report recognized traditional knowledge as an important information source for improving the understanding of climate change and other changes over time, and for developing comprehensive natural resource management and climate adaptation strategies.[29]

Traditional knowledge is essential to the economic and cultural survival of indigenous peoples, and, arguably, cultures throughout the world.[30,31] Traditional knowledge has been defined as "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment."[1,12,32] From an indigenous perspective, traditional knowledge encompasses all that is known about the world around us and how to apply that knowledge in relation to those beings that share the world.[12,33] As the elders of these communities – the "knowledge keepers" – pass away, the continued existence and viability of traditional knowledge is threatened. Programs are needed to help preserve the diverse traditional teachings and employ them to strive for balance among the physical, the spiritual, emotional, and intellectual – all things that encompass "wolakota," meaning to be a complete human being.[34]

Many, if not all, indigenous resource managers believe their cultures already possess sufficient knowledge to respond to climate variation and change.[30,35] However, there are elements of traditional knowledge that are increasingly vulnerable with changing climatic conditions,[4] including cultural identities, ceremonies, and traditional ways of life.[36] The use of indigenous and traditional knowledge to address climate change issues in Indian country has been called "indigenuity" – indigenous knowledge plus ingenuity.[33]

Native cultures are directly tied to Native places and homelands, reflecting the indigenous perspective that includes the "power of place."[6,36,37] Many indigenous peoples regard all people, plants, and animals that share our world as relatives rather than resources. Language, ceremonies, cultures, practices, and food sources evolved in concert with the inhabitants, human and non-human, of specific homelands.[1,33] The wisdom and knowledge of Native people resides in songs, dances, art, language, and music that reflect these places. By regarding all things as relatives, not resources, natural laws dictate that people care for their relatives in responsible ways. *"When you say, 'my mother is in pain,' it's very different from saying 'the earth is experiencing climate change.'"*[38,39] As climate change increasingly threatens these Native places, cultural identities, and practices, documenting the impacts on traditional lifestyles would strengthen adaptive strategies.

Traditional knowledge has developed tangible and reliable methods for recording historic weather and climate variability and their impacts on native societies.[40] For example, tribal community historians (winter count keepers) on the northern Great Plains recorded pictographs on buffalo hides to remember the sequence of events that marked each year, dating back to the 1600s. These once-reliable methods are becoming increasingly more difficult to maintain and less reliable as time passes.[41]

There are recent examples, however, where traditional knowledge and western-based approaches are used together to address climate change and related impacts. For example, the Alaska Native Tribal Health Consortium chronicles climate change impacts on the landscape and on human health and also develops adaptation strategies.[1] This Consortium employs western science, traditional ecological knowledge, and a vast network of "Local Environmental Observers" to develop comprehensive, community-scaled climate change health assessments.[42] During a recent drought on the Navajo Reservation, traditional knowledge and western approaches were also applied together, as researchers worked with Navajo elders to observe meteorological and hydrological changes and other phenomena in an effort to assess and reduce disaster risks.[43]

Key Message 1: Forests, Fires, and Food

Observed and future impacts from climate change threaten Native Peoples' access to traditional foods such as fish, game, and wild and cultivated crops, which have provided sustenance as well as cultural, economic, medicinal, and community health for generations.

Climate change impacts on forests and ecosystems are expected to have direct effects on culturally important plant and animal species, which will affect tribal sovereignty, culture, and economies.[2,4] Warmer temperatures and more frequent drought are expected to cause dieback and tree loss of several tree and plant species (such as birch, brown ash, and sweet grass) important for Native artistic, cultural, and economic purposes, including tourism.[22] Tribal access to valued resources is threatened by climate change impacts causing habitat degradation, forest conversion, and extreme changes in ecosystem processes.[44]

Observed impacts from both the causes and consequences of climate change, and added stressors such as extractive industry practices on or near Native lands, include species loss and shifts in species range.[1,45,46,47] There have also been observed changes in the distribution and population density of wildlife species, contraction or expansion of some plant species' range, and the northward migration of some temperate forest species.[4,48] For example, moose populations in Maine and similar locations are expected to decline because of loss of preferred habitat and increased winter temperatures, which are enabling ticks to survive through the winter and causing damage from significant infestation of the moose.[22]

Harvesting traditional foods is important to Native Peoples' culture, health, and economic well being. In the Great Lakes region, wild rice is unable to grow in its traditional range due to warming winters and changing water levels.

Loss of biodiversity, changes in ranges and abundance of culturally important native plants and animals, increases in invasive species, bark beetle damage to forests, and increased risk of forest fires have been observed in the Southwest, across much of the West, and in Alaska (see also Appendix 3: Climate Science Supplement, Figure 31; Ch. 7: Forests; Ch. 8: Ecosystems).[4,30,48,49] Changes in ocean temperature and acidity affect distribution and abundance of important food sources, like fish and shellfish (Ch. 2: Our Changing Climate; Ch. 24: Oceans).

Rising temperatures and hotter, drier summers are projected to increase the frequency and intensity of large wildfires (see Ch. 7: Forests).[44] Warmer, drier, and longer fire seasons and increased forest fuel load will lead to insect outbreaks and the spread of invasive species, dry grasses, and other fuel sources (see Ch. 7: Forests). Wildfire threatens Native and tribal homes, safety, economies, culturally important species, medicinal plants, traditional foods, and cultural sites. *"Fire affects the plants, which affect the water, which affects the fish, which affect terrestrial plants and animals, all of which the Karuk rely on for cultural perpetuity."*[50]

In interior Alaska, rural Native communities are experiencing new risks associated with climate change related wildfires in boreal forests and Arctic tundra (see also Ch. 22: Alaska).[1,51] Reliance on local, wild foods and the isolated nature of these communities, coupled with their varied preparedness and limited ability to deal with wildfires, leaves many communities at an increased risk of devastation brought on by fires. While efforts are being made to better coordinate rural responses to wildfires in Alaska, current responses are limited by organization and geographic isolation.[48]

Indigenous peoples have historically depended on the gathering and preparation of a wide variety of local plant and animal species for food (frequently referred to as traditional foods), medicines, ceremonies, community cohesion, and economic health for countless generations.[2,52] These include corn, beans, squash, seals, fish, shellfish, bison, bear, caribou, walrus, moose, deer, wild rice, cottonwood trees, and a multitude of native flora and fauna.[2,45,47,49,52,53,54,55,56,57] A changing climate affects the availability, tribal access to, and health of these resources.[1,2,4,47,57,58,59,60] This in turn threatens tribal customs, cultures, and identity.

Medicinal and food plants are becoming increasingly difficult to find or are no longer found in historical ranges.[2,56] For example, climate change and other environmental stressors are affecting the range, quality, and quantity of berry resources for the Wabanaki tribes in the Northeast.[2,61] The Karuk people in California have experienced a near elimination of both salmonids and acorns, which comprise 50% of a traditional Karuk diet.[62] In the Great Lakes region, wild rice is unable to grow in its traditional range due to warming winters and changing water levels, affecting the Anishinaabe peoples' culture, health, and well-being.[54]

Subsequent shifts from traditional lifestyles and diet, compounded by persistent poverty, food insecurity, the cost of non-traditional foods, and poor housing conditions have led to increasing health problems in communities, also increasing the risk to food and resource security.[1,2,16] Climate change is likely to amplify other indirect effects to traditional foods and resources, including limited access to gathering places and hunting grounds and environmental pollution.[4,57,59]


©David McLain/Aurora Photos

Human-caused stresses such as dam building have greatly reduced salmon on the Klamath River.

Key Message 2: Water Quality and Quantity

A significant decrease in water quality and quantity due to a variety of factors, including climate change, is affecting drinking water, food, and cultures. Native communities' vulnerabilities and limited capacity to adapt to water-related challenges are exacerbated by historical and contemporary government policies and poor socioeconomic conditions.

Native communities and tribes in different parts of the U.S. have observed changes in precipitation affecting their water resources. On the Colorado Plateau, tribes have been experiencing drought for more than a decade.[63,64] Navajo elders have observed long-term decreases in annual snowfall over the past century, a transition from wet to dry conditions in the 1940s, and a decline in surface water features.[20] Changes in long-term average temperature and precipitation have produced changes in the physical and hydrologic environment, making the Navajo Nation more susceptible to drought impacts, and some springs and shallow water wells on the Navajo Nation have gone dry.[43] Southwest tribes have observed damage to their agriculture and livestock, the loss of springs and medicinal and culturally important plants and animals, and impacts on drinking water supplies.[63,64,65,66] In the Northwest, tribal treaty rights to traditional territories and resources are being affected by the reduction of rainfall and snowmelt in the mountains, melting glaciers, rising temperatures, and shifts in ocean currents.[52,58,67] In Hawai'i, Native peoples have observed a shortening of the rainy season, increasing intensity of storms and flooding, and a rainfall pattern that has become unpredictable.[38] In Alaska, water availability, quality, and quantity are threatened by the consequences of permafrost thaw, which has damaged community water infrastructure, as well as by the northward extension of diseases such as those caused by the *Giardia* parasite, a result of disease-carriers like beavers moving northward in response to rising temperatures.[68] The impact of historical federal policies, such as the late 1800s allotment policy and practices regarding Native access to treaty-protected resources,[69] reverberate in current practices, such as states and the government permitting oil drilling and hydraulic fracturing on lands in and around reservations but outside of tribal jurisdiction (for example, a 2013 pipeline spill upstream of tribal reservations in Western North Dakota, and others). Such policies and practices exacerbate the threat to water quality and quantity for Native communities.


©Ted Wood Photography

Coal plant and fishermen, Navajo Reservation

Native American tribes have unique and significant adaptation needs related to climate impacts on water.[66] There is little available data to establish baseline climatic conditions on tribal lands, and many tribes do not have sufficient capacity to monitor changing conditions.[63] Without scientific monitoring, tribal decision-makers lack the data needed to quantify and evaluate current conditions and emerging trends in precipitation, streamflow, and soil moisture, and to plan and manage resources accordingly.[10,64,66] However, some existing efforts to document climate impacts on water resources could be replicated in other regions to assess hydrologic vulnerabilities.[58]

Water infrastructure is in disrepair or lacking on some reservations.[43,70] Approximately 30% of people on the Navajo Nation are not served by municipal systems and must haul water to meet their daily needs.[19,43] Longer-term impacts of this lack of control over water access are projected to include loss of traditional agricultural crops.[19,43] Furthermore, there is an overall lack of financial resources to support basic water infrastructure on tribal lands.[63] Uncertainty associated with undefined tribal water rights make it difficult to determine strategies to deal with water resource issues.[70] Potential impacts to treaty rights and water resources exist, such as a reduction of groundwater and drinking water availability and water quality decline, including impacts from oil and natural gas extraction and sea level rise-induced saltwater intrusion into coastal freshwater aquifers (see also Ch. 3: Water).[7] New datasets on climate impacts on water in many locations throughout Indian Country, such as the need to quantify available water and aquifer monitoring, will be important for improved adaptive planning.

Sand Dune Expansion

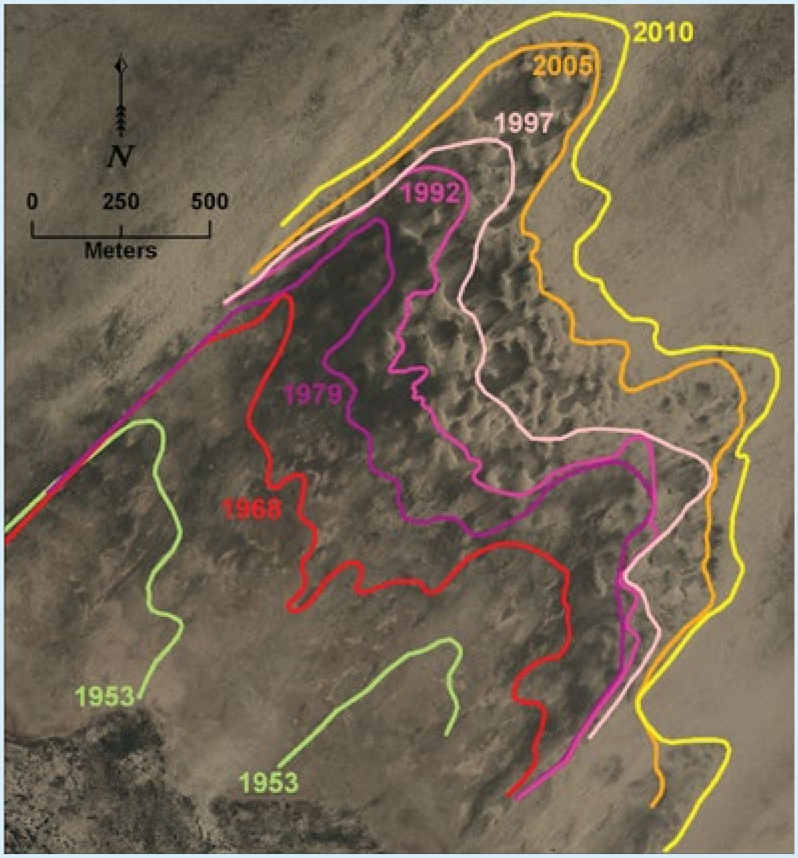

Figure 12.3. On the Arizona portion of the Navajo Nation, recurring drought and rising temperatures have accelerated growth and movement of sand dunes. Map above shows range and movement of Great Falls Dune Field from 1953 to 2010. Moving and/or growing dunes can threaten roads, homes, traditional grazing areas, and other tribal assets. (Figure source: Redsteer et al. 2011[55]).

Key Message 3: Declining Sea Ice

Declining sea ice in Alaska is causing significant impacts to Native communities, including increasingly risky travel and hunting conditions, damage and loss to settlements, food insecurity, and socioeconomic and health impacts from loss of cultures, traditional knowledge, and homelands.

> *"…since the late 1970s, communities along the coast of the northern Bering and Chukchi Seas have noticed substantial changes in the ocean and the animals that live there. While we are used to changes from year-to-year in weather, hunting conditions, ice patterns, and animal populations, the past two decades have seen clear trends in many environmental factors. If these trends continue, we can expect major, perhaps irreversible, impacts to our communities…."*
>
> – C. Pungowiyi, personal communication[71]

Scientists across the Arctic have documented rising regional temperatures over the past few decades at twice the global rate, and indigenous Arctic communities have observed these changes in their daily lives.[1] This temperature increase – which is expected to continue with future climate change – is accompanied by significant reductions in sea ice thickness and extent, increased permafrost thaw, more extreme weather and severe storms, and changes in seasonal ice melt/freeze of lakes and rivers, water temperature, sea level rise, flooding patterns, erosion, and snowfall timing and type (see also Ch. 2:

Sea Ice Cover Reaches Record Low

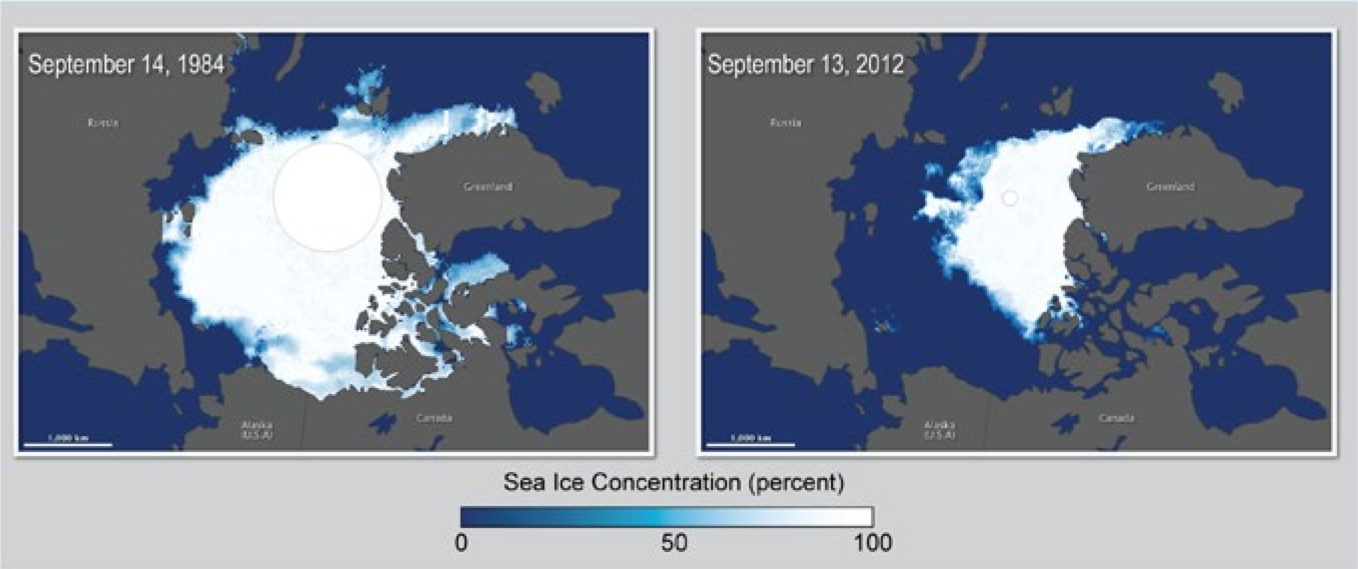

Figure 12.4. In August and September 2012, sea ice covered less of the Arctic Ocean than any time since the beginning of reliable satellite measurements (1979). The long-term retreat of sea ice has occurred faster than climate models had predicted. The average minimum extent of sea ice for 1979-2000 was 2.59 million square miles. The image on the left shows Arctic minimum sea ice extent in 1984, which was about the average minimum extent for 1979-2000. The image on the right shows that the extent of sea ice had dropped to 1.32 million square miles at the end of summer 2012. Alaska Native coastal communities rely on sea ice for many reasons, including its role as a buffer against coastal erosion from storms. (Figure source: NASA Earth Observatory 2012[77]).

Arctic Marine Food Web

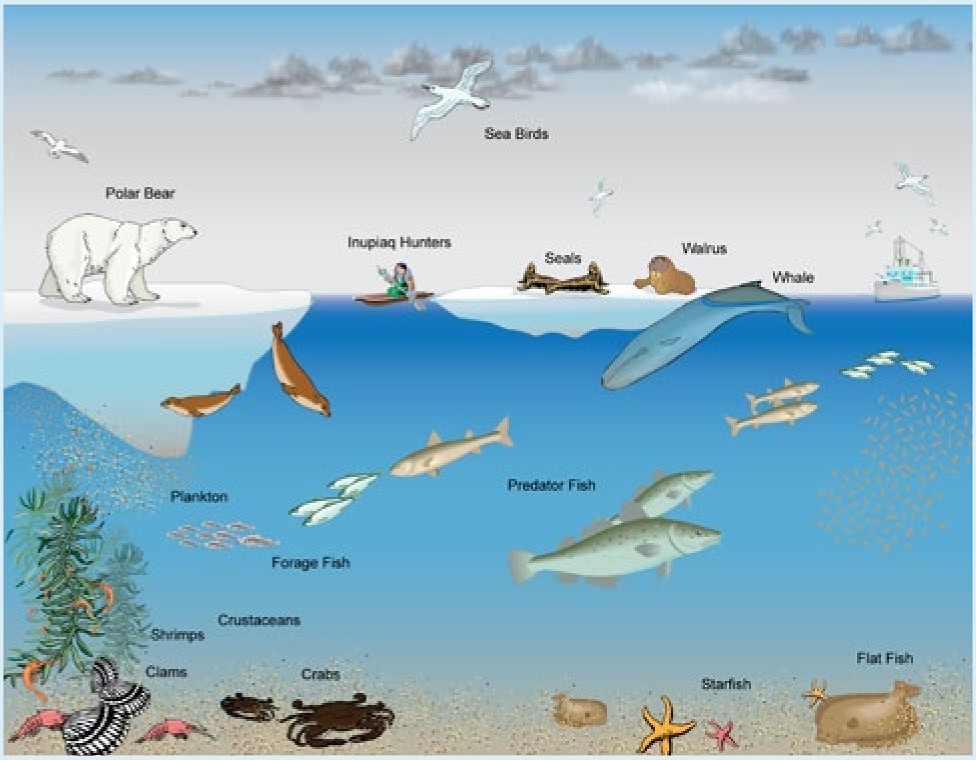

Figure 12.5. Dramatic reductions in Arctic sea ice and changes in its timing and composition affect the entire food web, including many Inupiaq communities that continue to rely heavily on subsistence hunting and fishing. (Figure source: NOAA NCDC).

Our Changing Climate).[71,72,73,74,75] These climate-driven changes in turn increase the number of serious problems for Alaska Native populations, which include injury from extreme or unpredictable weather and thinning sea ice, which can trap people far from home; changing snow and ice conditions that limit safe hunting, fishing, or herding practices; malnutrition and food insecurity from lack of access to subsistence food; contamination of food and water; increasing economic, mental, and social problems from loss of culture and traditional livelihood; increases in infectious diseases; and the loss of buildings and infrastructure from permafrost erosion and thawing, resulting in the relocation of entire communities (Ch. 22: Alaska).[1,68,71,75,76]

Alaska Native Inupiat and Yup'ik experts and scientists have observed stronger winds than in previous decades,[71,75,78] observations that are consistent with scientific findings showing changing Arctic wind patterns, which in turn influence loss of sea ice and shifts in North American and European weather.[79] They also observe accelerated melting of ice and snow, and movement of ice and marine mammals far beyond accessible range for Native hunters.[1] Thinning sea ice, earlier ice break-up, increasing temperatures, and changes in precipitation (for example, in the timing and amount of snow) also cause changes in critical feeding, resting, breeding, and denning habitats for arctic mammals important as subsistence foods, like polar bears, walrus, and seals.[1,73,75,80]

Key Message 4: Permafrost Thaw

Alaska Native communities are increasingly exposed to health and livelihood hazards from increasing temperatures and thawing permafrost, which are damaging critical infrastructure, adding to other stressors on traditional lifestyles.

The increased thawing of permafrost (permanently frozen soil) along the coasts and rivers is an especially potent threat to Alaska Native villages because it causes serious erosion, flooding, and destruction of homes, buildings, and roads from differential settlement, slumping, and/or collapse of underlying base sediments (see Ch. 2: Our Changing Climate; Ch.22: Alaska, Key Message 3).[81] This loss of infrastructure is further exacerbated by loss of land-fast sea ice, sea level rise, and severe storms.[1,82,83] At this time, more than 30 Native villages in Alaska (such as Newtok and Shishmaref) are either in need of, or in the process of, relocating their entire village.[1,84]

Serious public health issues arise due to damaged infrastructure caused by these multiple erosion threats. Among them are loss of clean water for drinking and hygiene, saltwater intrusion, and sewage contamination that could cause respiratory and gastrointestinal infections, pneumonia, and skin infections.[1,76,82,85] In addition, permafrost thaw is causing food insecurity in Alaska Native communities due to the thawing of ice cellars or ice houses used for subsistence food storage. This in turn leads to food contamination and sickness as well as dependence upon expensive, less healthy, non-traditional "store-bought" foods.[1,85,86]

Thawing Permafrost in Alaska

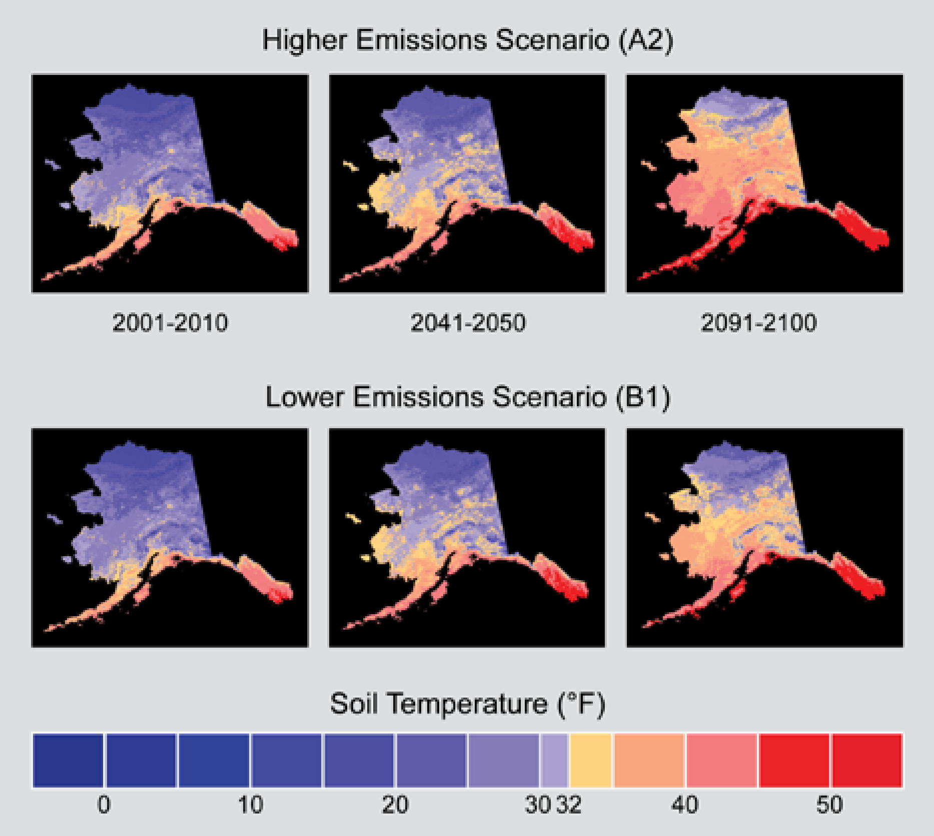

Figure 12.6. The maps show projected ground temperature at a depth of 3.3 feet assuming continued increases in emissions (A2 scenario) and assuming a substantial reduction in emissions (B1 scenario). Blue shades represent areas below freezing at a depth of 3.3 feet and yellow and red shades represent areas above freezing at that depth (see Ch. 22: Alaska for more details). Many Alaska Natives depend on permafrost for ice cellars to store frozen food, and replacing these cellars with electricity-driven freezers is expensive or otherwise infeasible. Permafrost thawing also affects infrastructure like roads and utility lines. (Figure source: Permafrost Lab, Geophysical Institute, University of Alaska Fairbanks).

Key Message 5: Relocation

Climate change related impacts are forcing relocation of tribal and indigenous communities, especially in coastal locations. These relocations, and the lack of governance mechanisms or funding to support them, are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.

Native peoples are no strangers to relocation and its consequences on their communities. Many eastern and southeastern tribal communities were forced to relocate to Canada or the western Great Lakes in the late 1700s and early 1800s and, later, to Oklahoma, compelling them to adjust and adapt to new and unfamiliar landscapes, subsistence resources, and climatic conditions. Forced relocations have continued into more recent times as well.[87] Now, many Native peoples in Alaska and other parts of the coastal United States, such as the Southeast and Pacific Northwest, are facing relocation as a consequence of climate change and additional stressors, such as food insecurity and unsustainable development and extractive practices on or near Native lands; such forms of displacement are leading to severe livelihood, health, and socio-cultural impacts on the communities.[1,3,23,38,45,88,89,90,91]

For example, Newtok, a traditional Yup'ik village in Alaska, is experiencing accelerated rates of erosion caused by the combination of decreased Arctic sea ice, thawing permafrost, and extreme weather events (Ch. 22: Alaska).[1,3] As a result, the community has lost critical basic necessities and infrastructure. While progress has been made toward relocation, limitations of existing federal and state statutes and regulations have impeded their efforts, and the absence of legal authority and a governance structure to facilitate relocation are significant barriers to the relocation of Newtok and other Alaska Native villages.[3,88,92] Tribal communities in coastal Louisiana are experiencing climate change induced rising sea levels, along with saltwater intrusion, subsidence, and intense erosion and land loss due to oil and gas extraction, levees, dams, and other river management techniques, forcing them to either relocate or try to find ways to save their land.[3,45] Tribal communities in Florida are facing potential displacement due to the risk of rising sea levels and saltwater intrusion inundating their reservation lands.[93] The Quileute tribe in northern Washington is responding to increased winter storms and flooding connected with increased precipitation by relocating some of their village homes and buildings to higher ground within 772 acres of Olympic National Park that has been transferred to them; the Hoh tribe is also looking at similar options for relocation.[90,94,95] Native Pacific Island communities, including those in Hawai'i and the U.S. affiliated Pacific Islands, are also being forced to consider relocation plans due to increasing sea level rise and storm surges.[38,96] While many Native communities are not necessarily being forced to relocate, they are experiencing other social and cultural forms of displacement. For example, rising sea levels are expected to damage Native coastal middens (sites reflecting past human activity such as food preparation) as well as Wabanaki coastal petroglyphs, leading to loss of culture and connection to their past for Northeast tribes.[22]

Rising temperatures are causing damage in Native villages in Alaska as sea ice declines and permafrost thaws. Resident of Selawik, Alaska, and his granddaughter survey a water line sinking into the thawing permafrost, August 2011.

Currently, the U.S. lacks an institutional framework to relocate entire communities. National, state, local, and tribal government agencies lack the legal authority and the technical, organizational, and financial capacity to implement relocation processes for communities forcibly displaced by climate change.[3,12] New governance institutions, frameworks, and funding mechanisms are needed to specifically respond to the increasing necessity for climate change induced relocation.[3,88] To be effective and culturally appropriate, it is important that such institutional frameworks recognize the sovereignty of tribal governments and that any institutional development stems from significant engagement with tribal representatives.[12]

> *"In Indigenous cultures, it is understood that ecosystems are chaotic, complex, organic, in a constant state of flux, and filled with diversity. No one part of an ecosystem is considered more important than another part and all parts have synergistic roles to play. Indigenous communities say that 'all things are connected' – the land to the air and water, the earth to the sky, the plants to the animals, the people to the spirit."*
>
> *– Patricia Cochran, Inupiat Leader*[97]

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

A central component of the assessment process was participation by members of the Chapter Author Team in a number of climate change meetings attended by indigenous peoples and other interested parties, focusing on issues relevant to tribal and indigenous peoples. These meetings included:

Oklahoma Inter-Tribal Meeting on Climate Variability and Change held on December 12, 2011, at the National Weather Center, Norman, OK, attended by 73 people.[56]

Indigenous Knowledge and Education (IKE) Hui Climate Change and Indigenous Cultures forum held in January 2012 in Hawai‘i and attended by 36 people.[38]

Alaska Forum on the Environment held from February 6-10, 2012, at the Dena’ina Convention Center in Anchorage, Alaska, and attended by about 1400 people with approximately 30 to 60 people per session.[27]

Stories of Change: Coastal Louisiana Tribal Communities’ Experiences of a Transforming Environment, a workshop held from January 22-27, 2012, in Pointe-au-Chien, Louisiana, and attended by 47 people.[45]

American Indian Alaska Native Climate Change Working Group 2012 Spring Meeting held from April 23–24, 2012, at the Desert Diamond Hotel-Casino in Tucson, Arizona, and attended by 80 people.[98]

First Stewards Symposium. First Stewards: Coastal Peoples Address Climate Change. National Museum of the American Indian, Washington DC. July 17-20, 2012.[30]

In developing key messages, the Chapter Author Team engaged in multiple technical discussions via teleconferences from August 2011 to March 2012 as they reviewed more than 200 technical inputs provided by the public, as well as other published literature and professional judgment. Subsequently, the Chapter Author Team teleconferenced weekly between March and July 2012 for expert deliberations of draft key messages by the authors. Each key message was defended by the entire author team before being selected for inclusion in the chapter report. These discussions were supported by targeted consultation with additional experts by the lead author of each message.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Observed and future impacts from climate change threaten Native Peoples’ access to traditional foods such as fish, game, and wild and cultivated crops, which have provided sustenance as well as cultural, economic, medicinal, and community health for generations.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe loss of biodiversity, impacts on culturally important native plants and animals, increases in invasive species, bark beetle damage to forests, and increased risk of forest fires that have been observed across the United States.[4,7,22,49,52,58]

Climate drivers associated with this key message are also discussed in Ch. 2: Our Changing Climate.

There are also many relevant and recent peer-reviewed publications[1,2,4,48,52,58,66] describing the northward migration of the boreal forest and changes in the distribution and density of wildlife species that have been observed.

Observed impacts on plant and animal species important to traditional foods, ceremonies, medicinal, cultural and economic well-being, including species loss and shifts in species range, are well-documented.[1,2,4,6,7,22,45,46,47,52]

New information and remaining uncertainties

A key uncertainty is how indigenous people will adapt to climate change, given their reliance on local, wild foods and the isolated nature of some communities, coupled with their varied preparedness and limited ability to deal with wildfires. Increased wildfire occurrences may affect tribal homes, safety, economy, culturally important species, medicinal plants, traditional foods, and cultural sites.

There is uncertainty as to the extent that climate change will affect Native American and Alaska Natives' access to traditional foods such as salmon, shellfish, crops, and marine mammals, which have provided sustenance as well as cultural, economic, medicinal, and community health for countless generations.

Assessment of confidence based on evidence

Based on the evidence and remaining uncertainties, confidence is **very high** that observed and future impacts from climate change, such as increased frequency and intensity of wildfires, higher temperatures, changes in sea ice, and ecosystem changes, such as forest loss and habitat damage, are threatening Native American and Alaska Natives' access to traditional foods such as salmon, shellfish, crops, and marine mammals, which have provided sustenance as well as cultural, economic, medicinal, and community health for countless generations.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

A significant decrease in water quality and quantity due to a variety of factors, including climate change, is affecting drinking water, food, and cultures. Native communities' vulnerabilities and limited capacity to adapt to water-related challenges are exacerbated by historical and contemporary government policies and poor socioeconomic conditions.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

There are numerous examples of tribal observations of changes in precipitation, rainfall patterns, and storm intensity and impacts on surface water features, agriculture, grazing, medicinal and culturally important plants and animals, and water resources.[2,4,6,7,43,52,55,58,63,64,65,66]

Examples of ceremonies are included in the Oklahoma Inter-Tribal Meeting on Climate Variability and Change Meeting Summary Report.[56] Water is used for some ceremonies, so it can be problematic when there is not enough at the tribe's disposal.[52,56,66] More than one tribe at the meeting also expressed how heat has been a problem during ceremonies because the older citizens cannot go into lodges that lack air conditioning.[56]

New information and remaining uncertainties

There is limited data to establish baseline climatic conditions on tribal lands, and many tribes do not have sufficient capacity to monitor changing conditions.[10,52,63,66] Without monitoring, tribal decision-makers lack the data needed to quantify and evaluate the current conditions and emerging trends in precipitation, streamflow, and soil moisture, and to plan and manage resources accordingly.[10,52,64,66]

Water infrastructure is in disrepair or lacking on some reservations.[43,70] There is an overall lack of financial resources to support basic water infrastructure on tribal lands, such as is found in the Southwest.[63]

Tribes that rely on water resources to maintain their cultures, religions, and life ways are especially vulnerable to climate change. Monitoring data is needed to establish baseline climatic conditions and to monitor changing conditions on tribal lands. Uncertainty associated with undefined tribal water rights makes it difficult to determine strategies to deal with water resource issues.[70]

Assessment of confidence based on evidence

Based on the evidence and remaining uncertainties, confidence is **very high** that decreases in water quality and quantity are affecting Native Americans and Alaska Natives' drinking water supplies, food, cultures, ceremonies, and traditional ways of life. Based upon extensive evidence, there is **very high** confidence that Native communities' vulnerabilities and lack of capacity to adapt to climate change are exacerbated by historical and contemporary federal and state land-use policies and practices, political marginalization, legal issues associated with tribal water rights, water infrastructure deficiencies, and poor socioeconomic conditions.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Declining sea ice in Alaska is causing significant impacts to Native communities, including increasingly risky travel and hunting conditions, damage and loss to settlements, food insecurity, and socioeconomic and health impacts from loss of cultures, traditional knowledge, and homelands.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that summer sea ice is rapidly declining is based on satellite data and other observational data and is incontrovertible. The seasonal pattern of observed loss of Arctic sea ice is generally consistent with simulations by global climate models, in which the extent of sea ice decreases more rapidly in summer than in winter (Ch. 2: Our Changing Climate). Projections by these models indicate that the Arctic Ocean is projected to become virtually ice-free in summer before mid-century, and models that best match historical trends project a nearly sea ice-free Arctic in summer by the 2030s.[74] Extrapolation of the present observed trends suggests an even earlier ice-free Arctic in summer. (Ch. 2: Our Changing Climate and Ch. 22: Alaska).

Sea ice loss is altering marine ecosystems; allowing for greater ship access and new development; increasing Native community vulnerabilities due to changes in sea ice thickness and extent; destroying housing, village sanitation and other infrastructure (including entire villages); and increasing food insecurity due to lack of access to subsistence food and loss of cultural traditions. Evidence for all these impacts of sea ice loss is well-documented in field studies, indigenous knowledge, and scientific literature.[1,2,3,71,73,75,78]

New information and remaining uncertainties

A key uncertainty is how indigenous peoples will be able to maintain historical subsistence ways of life, which include hunting, fishing, harvesting, and sharing, and sustain the traditional relationship with the environment given the impacts from sea ice decline and changes. Increased sea ice changes and declines are already causing increasingly hazardous hunting and traveling conditions along ice edges; damage to homes and infrastructure from erosion; changes in habitat for subsistence foods and species, with overall impacts on food insecurity and for species necessary for medicines, ceremonies, and other traditions.[1] The effects of sea ice loss are exacerbated by other climate change driven impacts such as changes in snow and ice, weather, in-migration of people, poverty, lack of resources to respond to changes, and contamination of subsistence foods.[1,2]

Additional observations and monitoring are needed to more adequately document ice and weather changes.

Assessment of confidence based on evidence

Based on the evidence and remaining uncertainties, there is **very high** confidence that loss of sea ice is affecting the traditional life ways of Native communities in a number of important ways, such as more hazardous travel and hunting conditions along the ice edge; erosion damage to homes, infrastructure, and sanitation facilities (including loss of entire villages); changes in ecosystem habitats and, therefore, impacts on food security; and socioeconomic and health impacts from cultural and homeland losses.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Alaska Native communities are increasingly exposed to health and livelihood hazards from increasing temperatures and thawing permafrost, which are damaging critical infrastructure, adding to other stressors on traditional lifestyles.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Given the evidence base and uncertainties, confidence is high that rising temperatures are thawing permafrost and that this thawing is expected to continue (Ch. 2: Our Changing Climate) Permafrost temperatures are increasing over Alaska and much of the Arctic. Regions of discontinuous permafrost (where annual average soil temperatures of already close to 32°F) are highly vulnerable to thaw (Ch. 2: Our Changing Climate).[81]

There are also many relevant and recent peer-reviewed publications[1,3,82,83] describing the impact of permafrost thaw on Alaska Native villages. Over 30 Native villages in Alaska are in need of relocation or are in the process of being moved. Recent work[1,84,85] documents public health issues such as contamination of clean water for drinking and hygiene and food insecurity through thawing of ice cellars for subsistence food storage.

New information and remaining uncertainties

Improved models and observational data (see Ch. 22: Alaska) confirmed many of the findings from the prior 2009 Alaska assessment chapter, which informed the 2009 National Climate Assessment.[99]

A key uncertainty is how indigenous peoples in Alaska will be able to sustain traditional subsistence life ways when their communities and settlements on the historical lands of their ancestors are collapsing due to permafrost thawing, flooding, and erosion combined with loss of shore-fast ice, sea level rise, and severe storms, especially along the coasts and rivers.[1]

Another uncertainty is how indigenous communities can protect the health and welfare of the villagers from permafrost-thaw-caused public health issues of drinking water contamination, loss of traditional food storage, and potential food contamination.[1]

It is uncertain how Native communities will be able to effectively relocate and maintain their culture, particularly because there are no institutional frameworks, legal authorities, or funding to implement relocation for communities forced to relocate.[1,3,12]

Assessment of confidence based on evidence

Based on the evidence and remaining uncertainties, confidence is **very high** that Alaska Native communities are increasingly exposed to health and livelihood hazards from permafrost thawing and increasing temperatures, which are causing damage to roads, water supply and sanitation systems, homes, schools, ice cellars, and ice roads, and threatening traditional lifestyles.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Climate change related impacts are forcing relocation of tribal and indigenous communities, especially in coastal locations. These relocations, and the lack of governance mechanisms or funding to support them, are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in more than 200 technical input reports on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

There is well-documented evidence that tribal communities are vulnerable to coastal erosion that could force them to relocate.[1,3,23,38,88,89] For example, tribal communities in Alaska, such as Newtok, Kivalina, and Shishmaref, are experiencing accelerated rates of erosion caused by the combination of decreased Arctic sea ice, thawing permafrost, and extreme weather events, resulting in loss of basic necessities and infrastructure (see also Ch. 22: Alaska).[1,3,88,91]

Tribal communities in coastal Louisiana are experiencing climate-induced rising sea levels, along with saltwater intrusion and intense erosion and land loss due to oil and gas extraction and river management, forcing them to either relocate or try to find ways to save their land (see also Ch. 25: Coasts and Ch. 17 Southeast).[3,45] Tribal communities in Florida are facing potential displacement due to the risk of rising sea levels and saltwater intrusion inundating their reservation lands.[93] The Quileute tribe in northern Washington is relocating some of their village homes and buildings to Olympic National Park in response to increased winter storms and flooding connected with increased precipitation; the Hoh tribe is also considering similar options.[90,94]

Native Pacific Island communities are being forced to consider relocation plans due to increasing sea level rise and storm surges (see also Ch. 23: Hawai‘i and Pacific Islands).[38]

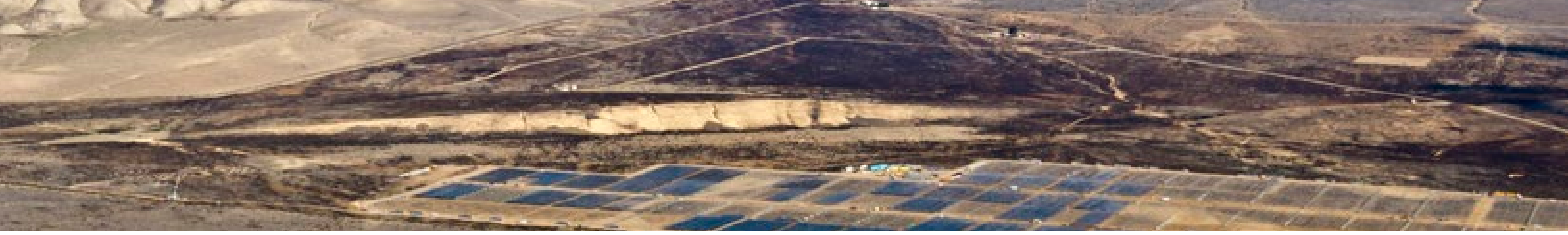
New information and remaining uncertainties

A key uncertainty is the extent to which the combination of other impacts (for example, erosion caused by dredging for oil pipelines or second-order effects from adaptation-related development projects) will coincide with sea level rise and other climate-related issues to increase the rate at which communities will need to relocate.[1,3,38]

Another key uncertainty is how communities will be able to effectively relocate, maintain their communities and culture, and reduce the impoverishment risks that often go along with relocation.[1,3,38] The United States lacks an institutional framework to relocate entire communities, and national, state, local, and tribal government agencies lack the legal authority and the technical, organizational, and financial capacity to implement relocation processes for communities forcibly displaced by climate change.[3,12]

Assessment of confidence based on evidence

Based on the evidence, there is **very high** confidence that tribal communities in Alaska, coastal Louisiana, Pacific Islands, and other coastal locations are being forced to relocate due to sea level rise, coastal erosion, melting permafrost, and/or extreme weather events. There is **very high** confidence that these relocations and the lack of governance mechanisms or funding to support them are causing loss of community and culture, health impacts, and economic decline, further exacerbating tribal impoverishment.



Climate Change Impacts in the United States

CHAPTER 13
LAND USE AND LAND COVER CHANGE

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On the Web: http://nca2014.globalchange.gov/report/sectors/land-use-and-land-cover-change

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

13 LAND USE
AND LAND COVER CHANGE

KEY MESSAGES

1. Choices about land-use and land-cover patterns have affected and will continue to affect how vulnerable or resilient human communities and ecosystems are to the effects of climate change.
2. Land-use and land-cover changes affect local, regional, and global climate processes.
3. Individuals, businesses, non-profits, and governments have the capacity to make land-use decisions to adapt to the effects of climate change.
4. Choices about land use and land management may provide a means of reducing atmospheric greenhouse gas levels.

In addition to emissions of heat-trapping greenhouse gases from energy, industrial, agricultural, and other activities, humans also affect climate through changes in land *use* (activities taking place on land, like growing food, cutting trees, or building cities) and land *cover* (the physical characteristics of the land surface, including grain crops, trees, or concrete).[1] For example, cities are warmer than the surrounding countryside because the greater extent of paved areas in cities affects how water and energy are exchanged between the land and the atmosphere. This increases the exposure of urban populations to the effects of extreme heat events. Decisions about land use and land cover can therefore affect, positively or negatively, how much our climate will change and what kind of vulnerabilities humans and natural systems will face as a result.

The impacts of changes in land use and land cover cut across all regions and sectors of the National Climate Assessment. Chapters addressing each region discuss land-use and land-cover topics of particular concern to specific regions. Similarly, chapters addressing sectors examine specific land-use matters. In particular, land cover and land use are a major focus for sectors such as agriculture, forests, rural and urban communities, and Native American lands. By contrast, the key messages of this chapter are national in scope and synthesize the findings of other chapters regarding land cover and land use.


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Land-use and land-cover changes affect climate processes: Above, development along Colorado's Front Range.

Land uses and land covers change over time in response to evolving economic, social, and biophysical conditions.[2] Many of these changes are set in motion by individual landowners and land managers and can be quantified from satellite measurements, aerial photographs, on-the-ground observations, and reports from landowners and users.[3,4] Over the past few decades, the most prominent land changes within the U.S. have been changes in the amount and kind of forest cover due to logging practices and development in the Southeast and Northwest and to urban expansion in the Northeast and Southwest.

Because humans control land use and, to a large extent, land cover, individuals, businesses, non-profit organizations, and governments can make land decisions to adapt to and/or reduce the effects of climate change. Often the same land-use decision can serve both aims. Adaptation options (those aimed at coping with the effects of climate change) include varying the local mix of vegetation and concrete to reduce heat in cities or elevating homes to reduce exposure to sea level rise or flooding. Land-use and land-cover-related options for mitigating climate change (reducing the speed and amount of climate change) include expanding forests to accelerate removal of carbon from the atmosphere, modifying the way cities are built and organized to reduce energy and motorized transportation demands, and altering agricultural management practices to increase carbon storage in soil.

Despite this range of climate change response options, there are three main reasons why private and public landowners may choose not to modify land uses and land covers for climate adaptation or mitigation purposes. First, land decisions are influenced not only by climate but also by economic, cultural, legal, or other considerations. In many cases, climate-based land-change efforts to adapt to or reduce climate change meet with resistance because current practices are too costly to modify and/or too deeply entrenched in local societies and cultures. Second, certain land uses and land covers are simply difficult to modify, regardless of desire or intent. For instance, the number of homes constructed in floodplains or the amount of irrigated agriculture can be so deeply rooted that they are difficult to change, no matter how much those practices might impede our ability to respond to climate change. Finally, the benefits of land-use decisions made by individual landowners with specific adaptation or mitigation goals do not always accrue to those landowners or even to their communities. Therefore, without some institutional intervention (such as incentives or penalties), the motivations for such decisions can be weak.

Recent Trends

In terms of land area, the U.S. remains a predominantly rural country, especially as its population increasingly gravitates towards urban areas. In 1910, only 46% of the U.S. population lived in urban areas, but by 2010 that figure had climbed to more than 81%.[5] In 2006 (the most recent year for which these data are available), more than 80% of the land cover in the lower 48 states was dominated by shrub/scrub vegetation, grasslands, forests, and agriculture.[6,7] Forests and grasslands, which include acreage used for timber production and grazing, account for more than half of all U.S. land use by area (Table 13.1), about 63% of which is in private ownership, though their distribution and ownership patterns vary regionally.[4] Agricultural land uses are carried out on 18% of U.S. surface area. Developed or built-up areas covered only about 5% of the country's land surface, with the greatest concentrations of urban areas in the Northeast, Midwest, and Southeast. This apparently small percentage of developed area belies its rapid expansion and does not include development that is dispersed in a mosaic among other land uses (like agriculture and forests). In particular, low-density housing developments (suburban and exurban areas), which are not well-represented in commonly used satellite measurements, have rapidly expanded throughout the U.S. over the last 60 years or so.[8,9] Based on Census data, areas settled at suburban and exurban densities (1 house per 1 to 40 acres on average) cover more than 15 times the land area settled at urban densities (1 house per acre or less) and covered five times more land area in 2000 than in 1950.[8]

Despite these rapid changes in developed land covers, the vast size of the country means that total land-cover changes in the U.S. may appear deceptively modest. Since 1973, satellite data show that the overall rate of land-cover changes nationally has averaged about 0.33% per year. Yet this small rate of change has produced a large cumulative impact. Between 1973 and 2000, 8.6% of the area of the lower 48 states experienced land-cover change, an area roughly equivalent to the combined land area of California and Oregon.[1]

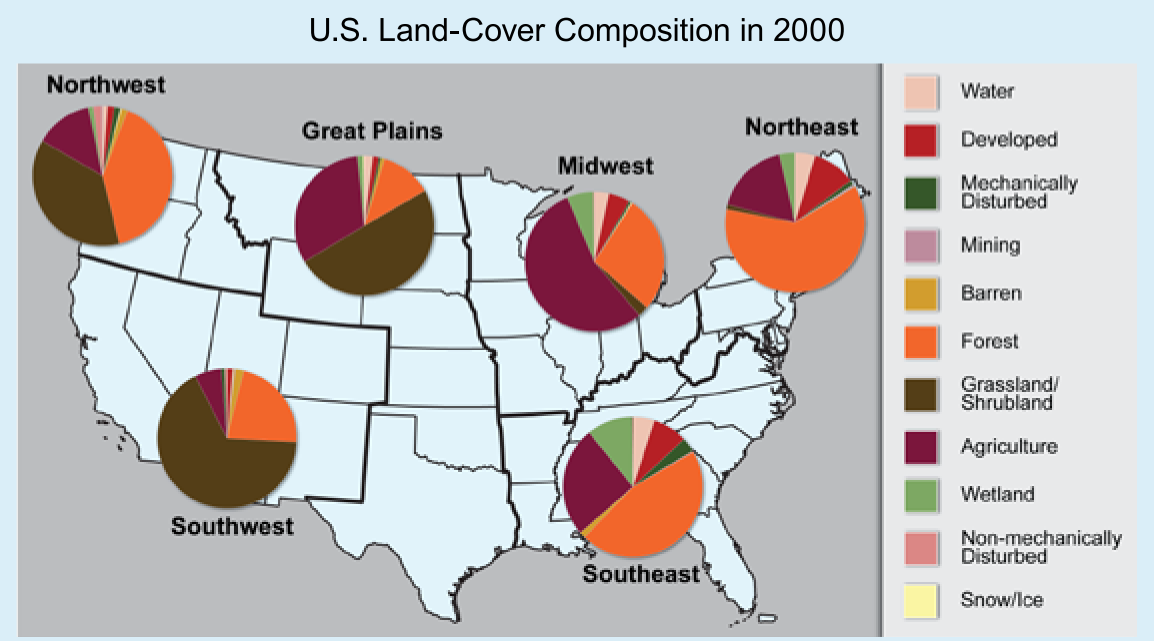

Figure 13.1. Map shows regional differences in land cover. These patterns affect climate and will be affected by climate change. They also influence the vulnerability and resilience of communities to the effects of climate change (Figure source: USGS Earth Resources Observation and Science (EROS) Center). (See Table 13.2 for definitions of mechanically and non-mechanically disturbed.)

These national-level annual rates of land changes mask considerable geographic variability in the types, rates, and causes of change.[3] Between 1973 and 2000, the Southeast region had the highest rate of change, due to active forest timber harvesting and replanting, while the Southwest region had the lowest rate of change.

Table 13.1. Circa-2001 land-cover statistics for the National Climate Assessment regions of the United States based on the National Land Cover Dataset,[7] and overall United States land-use statistics—circa 2007.[4]

Land Cover Class	Northeast	Southeast	Midwest	Great Plains	Southwest	Northwest	Alaska	Hawaii	United States	Land Use Class (ca 2007)	United States (ca 2007)
Agriculture	10.9%	23.0%	49.0%	29.7%	5.0%	10.0%	0.0%	4.0%	18.6%	Cropland	18.0%
Grassland, Shrub/Scrub, Moss, Lichen	3.4%	7.8%	2.9%	50.5%	65.7%	42.8%	44.9%	33.3%	39.2%	Grassland, Pasture, and Range	27.1%
Forest	52.4%	38.7%	23.7%	10.7%	19.9%	37.7%	22.4%	22.0%	23.2%[a]	Forest	29.7%[a]
Barren	0.8%	0.3%	0.2%	0.5%	3.7%	1.5%	7.7%	11.2%	2.6%	Special Use[b]	13.8%
Developed, Built-Up	9.6%	7.7%	8.0%	4.0%	2.7%	3.0%	0.1%	6.7%	4.0%	Urban	2.7%
Water, Ice, Snow	14.9%	7.3%	10.4%	1.9%	1.7%	3.2%	18.5%	21.7%	7.4%	Miscellaneous[c]	8.7%
Wetlands	8.0%	15.2%	5.8%	2.7%	0.7%	1.3%	6.4%	0.3%	5.0%		

[a] Definitional differences in the way certain categories are defined, such as the special uses distinction in the USDA Economic Research Service land use estimates, make direct comparisons between land use and land cover challenging. For example, forest land use (29.7%) exceeds forest cover (23.2%). Forest use definitions include lands where trees have been harvested and may be replanted, while forest cover is a measurement of the presence of trees.

[b] Special uses represent rural transportation, rural parks and wildlife, defense and industrial, plus miscellaneous farm and other special uses.

[c] Miscellaneous uses represent unclassified uses such as marshes, swamps, bare rock, deserts, tundra plus other uses not estimated, classified, or inventoried.

Table 13.2. Percentage change in land-cover type between 1973 and 2000 for the contiguous U.S. National Climate Assessment regions. These figures do not indicate the total amount of changes that have occurred, for example when increases in forest cover were offset by decreases in forest cover, and when cropland taken out of production was offset by other land being put into agricultural production. Data from USGS Land Cover Trends Project; Sleeter et al. 2013.[10]

Land Cover Type	Northeast	Southeast	Midwest	Great Plains	Southwest	Northwest
Grassland/Shrubland	0.73	0.31	0.59	1.55	-0.28	0.35
Forest	-2.02	-2.51	-0.93	-0.71	-0.49	2.39
Agriculture	-0.85	-1.62	-1.38	-1.60	-0.37	-0.35
Developed	1.36	2.28	1.34	0.43	0.51	0.51
Mining	0.14	-0.05	0.02	0.07	0.10	0.03
Barren	0.00	-0.01	0.00	0.00	0.00	0.00
Snow/Ice	0.00	0.00	0.00	0.00	0.00	0.00
Water	0.03	0.45	0.08	0.23	0.03	-0.02
Wetland	-0.05	-0.69	-0.05	-0.13	-0.02	0.03
Mechanically Disturbed[a]	0.66	1.76	0.32	0.11	0.07	0.07
Non-mechanically Disturbed[b]	0.00	0.07	0.01	0.06	0.46	1.78

[a] Land in an altered and often un-vegetated state that, because of disturbances by mechanical means, is in transition from one cover type to another. Mechanical disturbances include forest clear-cutting, earthmoving, scraping, chaining, reservoir drawdown, and other similar human-induced changes.

[b] Land in an altered and often un-vegetated state that because of disturbances by non-mechanical means, is in transition from one cover type to another. Non-mechanical disturbances are caused by fire, wind, floods, animals, and other similar phenomena.

Projections

Future patterns of land use and land cover will interact with climate changes to affect human communities and ecosystems. At the same time, future climate changes will also affect how and where humans live and use land for various purposes.

National-scale analyses suggest that the general historical trends of land-use and land-cover changes (described above) will continue, with some important regional differences. These projections all assume continued population growth based on assumed or statistically modeled rates of birth, death, and migration,[11] which will result in changes in land use and land cover that are spread unevenly across the country. Urban land covers are projected to increase in the lower 48 states by 73% to 98% (to between 10% and 12% of land area versus less than 6% in 1997) by 2050, using low versus high growth assumptions, respectively. The slowest rate of increase is in the Northeast region, because of the high level of existing development and relatively low rates of population growth, and the highest rate is in the Northwest. In terms of area, the Northwest has the smallest projected increase in urban area (approximately 4.2 million acres) and the Southeast the largest (approximately 27.5 million acres).[12]

Changes in development density will have an impact on how population is distributed and affects land use and land cover. Some of the projected changes in developed areas will depend on assumptions about changes in household size and how concentrated urban development will be. Higher population density means less land is converted from forests or grasslands, but results in a greater extent of paved area. Projections based on estimates of housing-unit density allow the assessment of impacts of urban land-use growth by density class. Increases in low-density exurban areas will result in a greater area affected by development and are expected to increase commuting times and infrastructure costs.

The areas projected to experience exurban development will have less density of impervious surfaces (like asphalt or concrete). While about one-third of exurban areas are covered by impervious surfaces,[13] urban or suburban areas are about one-half concrete and asphalt. Impervious surfaces have a wide range of environmental impacts and thus represent a key means by which developed lands modify the movement of water, energy, and living things. For example, areas with more impervious surfaces like parking lots and roads tend to experience more rapid runoff, greater risk of flooding, and higher temperatures from the urban heat-island effect.

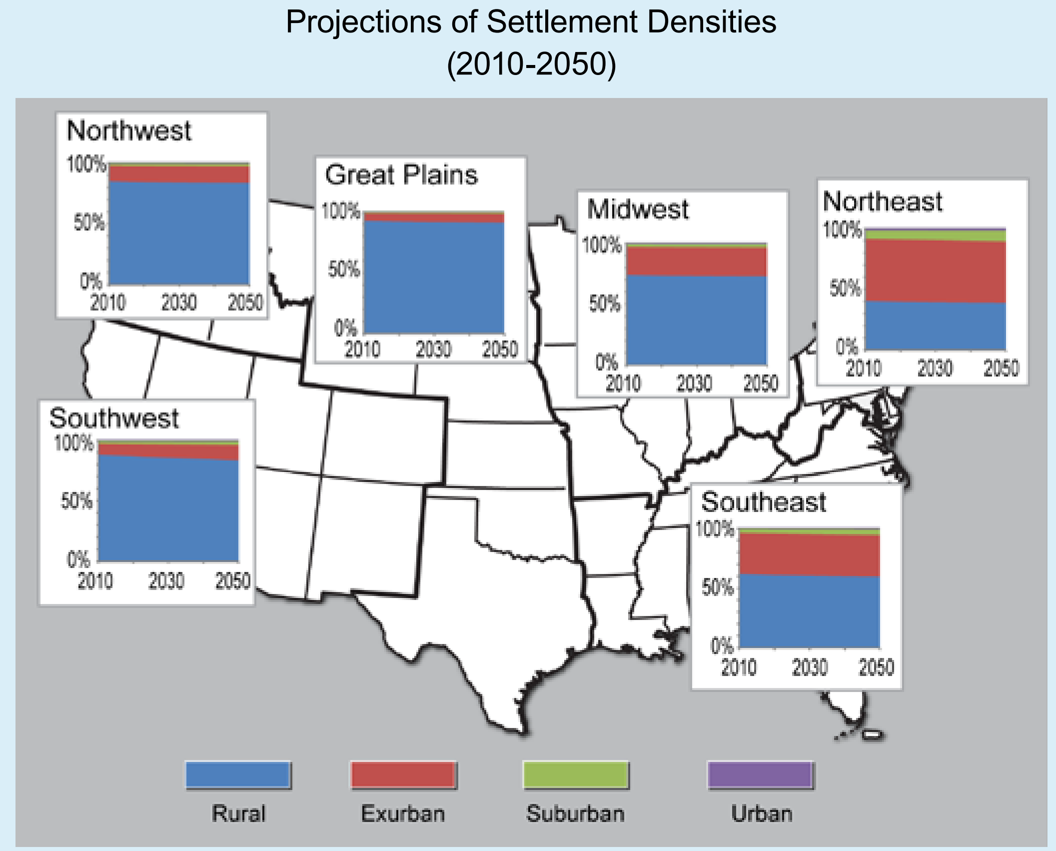

Figure 13.2. Projected percentages in each housing-unit density category for 2050 compared with 2010, assuming demographic and economic growth consistent with the high-growth emissions scenario (A2). (Data from U.S. EPA Integrated Climate and Land Use Scenarios).

Projections of both land-use and land-cover changes will depend to some degree on rates of population and economic growth. In general, scenarios that assume continued high growth produce more rapid increases in developed areas of all densities and in areas covered by impervious surfaces (paved areas and buildings) by 2050.[12,13]

Land-use scenarios project that exurban and suburban areas will expand nationally by 15% to 20% between 2000 and 2050,[13] based on high- and low-growth scenarios respectively. Land-cover projections by Wear[12] show that both cropland and forest are projected to decline most relative to 1997 (by 6% to 7%, respectively, by 2050) under a scenario of high population and economic growth and least (by 4% and 6%, respectively) under lower-growth scenarios. More forest than cropland is projected to be lost in the Northeast and Southeast, whereas more cropland than forest is projected to be lost in the Midwest and Great Plains.[14] Some of these regional differences are due to the current mix of land uses, others to the differential rates of urbanization in these different regions.

Projected Land Covers (2010-2050)

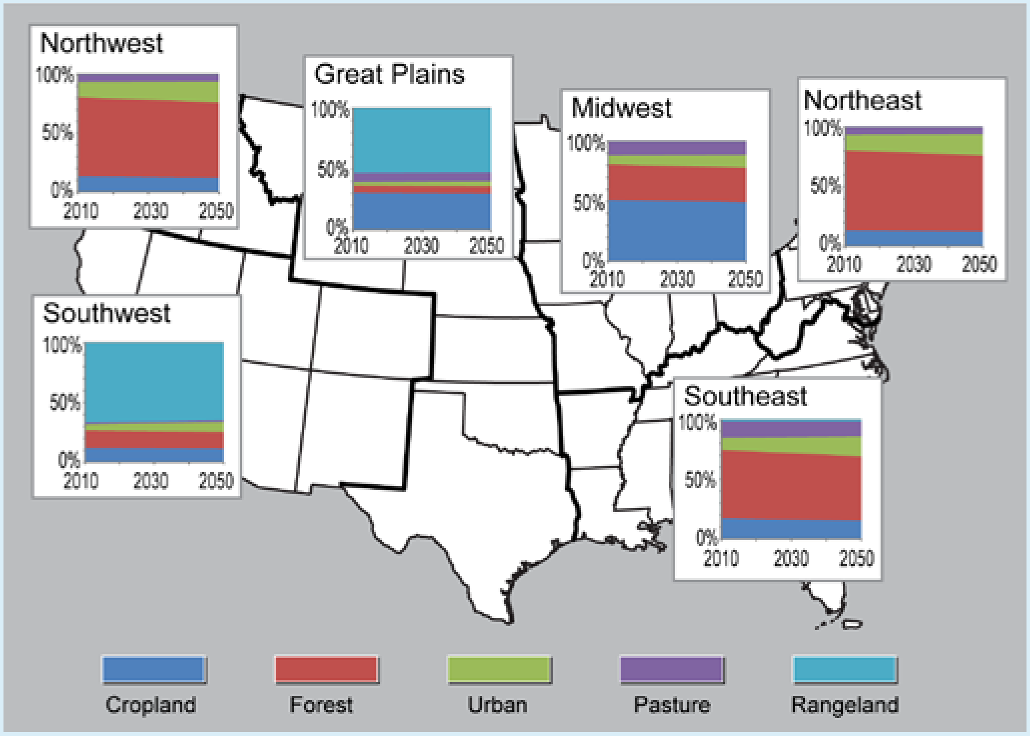

Figure 13.3. Projected percentages in each land-cover category for 2050 compared with 2010, assuming demographic and economic growth consistent with the high-growth emissions scenario (A2) (Data from USDA).

Key Message 1: Effects on Communities and Ecosystems

Choices about land-use and land-cover patterns have affected and will continue to affect how vulnerable or resilient human communities and ecosystems are to the effects of climate change.

Decisions about land-use and land-cover change by individual landowners and land managers are influenced by demographic and economic trends and social preferences, which unfold at global, national, regional, and local scales. Policymakers can directly affect land use and land cover. For example, Congress can declare an area as federally protected wilderness, or local officials can set aside portions of a town for industrial development and create tax benefits for companies to build there. Climate factors typically play a secondary role in land decisions, if they are considered at all. Nonetheless, land-change decisions may affect the vulnerabilities of individuals, households, communities, businesses, non-profit organizations, and ecosystems to the effects of climate change.[15] A farmer's choice of crop rotation in response to price signals affects his or her farm income's susceptibility to drought, for example. Such choices, along with changes in climate can also affect the farm's demand for water for irrigation. Similarly, a developer's decision to build new homes in a floodplain may affect the new homeowners' vulnerabilities to flooding events. A decision to include culverts underneath a coastal roadway may facilitate migration of a salt marsh inland as sea level rises.

The combination of residential location choices with wildfire occurrence dramatically illustrates how the interactions between land use and climate processes can affect climate change impacts and vulnerabilities. Low-density (suburban and exurban) housing patterns in the U.S. have expanded and are projected to continue to expand.[13] One result is a rise in the amount of construction in forests and other wildlands[16] that in turn has increased the exposure of houses, other structures, and people to damages from wildfires, which are increasing. The number of buildings lost in the 25 most destructive fires in California history increased significantly in the 1990s and 2000s compared to the previous three decades.[17] These losses are one example of how changing development patterns can interact with a changing climate to create dramatic new risks. In the western United States, increasing frequencies of large wildfires and longer wildfire durations are strongly associated with increased spring and summer temperatures and an earlier

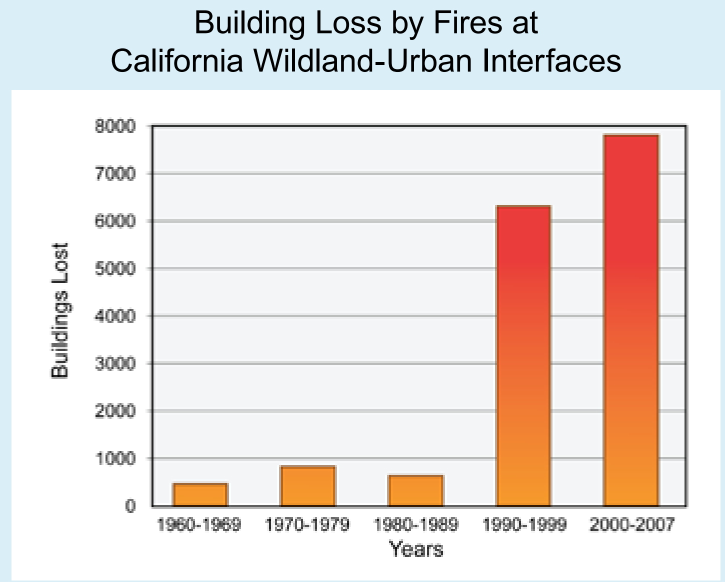

Figure 13.4. Many forested areas in the U.S. have experienced a recent building boom in what is known as the "wildland-urban interface." This figure shows the number of buildings lost from the 25 most destructive wildland-urban interface fires in California history from 1960 to 2007 (Figure source: Stephens et al. 2009[17]).


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Construction near forests and wildlands is growing. Here, wildfire approaches a housing development.

spring snowmelt.[18] The effects on property loss of increases in the frequency and sizes of fires under climate change are also projected to increase in the coming decades because so many more people will have moved into increasingly fire-prone places (Ch. 2: Our Changing Climate; Ch. 7: Forests).

Key Message 2: Effects on Climate Processes

Land-use and land-cover changes affect local, regional, and global climate processes.

Land use and land cover play critical roles in the interaction between the land and the atmosphere, influencing climate at local, regional, and global scales.[19] There is growing evidence that land use, land cover, and land management affect the U.S. climate in several ways:

- Air temperature and near-surface moisture are changed in areas where natural vegetation is converted to agriculture.[20,21] This effect has been observed in the Great Plains and the Midwest, where overall dew point temperatures or the frequency of occurrences of extreme dew point temperatures have increased due to converting land to agricultural use.[21,22,23] This effect has also been observed where the fringes of California's Central Valley are being converted from natural vegetation to agriculture.[24] Other areas where uncultivated and conservation lands are being returned to cultivation, for example from restored grassland into biofuel production, have also experienced temperature shifts. Regional daily maximum temperatures were lowered due to forest clearing for agriculture in the Northeast and Midwest, and then increased in the Northeast following regrowth of forests due to abandonment of agriculture.[25]

- Conversion of rain-fed cropland to irrigated agriculture further intensifies the impacts of agricultural conversion on temperature. For example, irrigation in California has been found to reduce daily maximum temperatures by up to 9°F.[26] Model comparisons suggest that irrigation cools temperatures directly over croplands in California's Central Valley by 5°F to 13°F and increases relative humidity by 9% to 20%.[27] Observational data-based studies found similar impacts of irrigated agriculture in the Great Plains.[22,28]

- Both observational and modeling studies show that introduction of irrigated agriculture can alter regional precipitation.[29,30] It has been shown that irrigation in the Ogallala aquifer portion of the Great Plains can affect precipitation as far away as Indiana and western Kentucky.[30]

- Urbanization is having significant local impacts on weather and climate. Land-cover changes associated with urbanization are creating higher air temperatures compared to the surrounding rural area.[31,32] This is known as the "urban heat island" effect (see Ch. 9: Human Health). Urban landscapes are also affecting formation of convective storms and changing the location and amounts of precipitation compared to pre-urbanization.[32,33]

- Land-use and land-cover changes are affecting global atmospheric concentrations of greenhouse gases. The impact is expected to be most significant in areas with forest loss or gain, where the amount of carbon that can be transferred from the atmosphere to the land (or from the land to the atmosphere) is modified. Even in relatively un-forested areas, this effect can be significant. A recent USGS report suggests that from 2001 to 2005 in the Great Plains between 22 to 106 million metric tons of carbon were stored in the biosphere due to changes in land use and climate.[34] Even with these seemingly large numbers, U.S. forests absorb only 7% to 24% (with a best estimate of 16%) of fossil fuel CO_2 emissions (see Ch. 15: Biogeochemical Cycles, "Estimating the U.S. Carbon Sink").

Key Message 3: Adapting to Climate Change

Individuals, businesses, non-profits, and governments have the capacity to make land-use decisions to adapt to the effects of climate change.

Land-use and land-cover patterns may be modified to adapt to anticipated or observed effects of a changed climate. These changes may be either encouraged or mandated by government (whether at federal or other levels), or undertaken by private initiative. In the U.S., even though land-use decisions are highly decentralized and strongly influenced by Constitutional protection of private property, the Supreme Court has also defined a role for government input into some land-use decisions.[35] Thus on the one hand farmers may make private decisions to plant different crops in response to changing growing conditions and/or market prices. On the other hand, homeowners may be compelled to respond to policies, zoning, or regulations (at national, state, county, or municipal levels) by elevating their houses to reduce flood impacts associated with more intense rainfall events and/or increased impervious surfaces.

Land-use and land-cover changes are thus rarely the product of a single factor. Land-use decision processes are influenced not only by the biophysical environment, but also by markets, laws, technology, politics, perceptions, and culture. Yet there is evidence that climate adaptation considerations are playing an increasingly large role in land decisions, even in the absence of a formal federal climate policy. Motivations typically include avoiding or reducing negative impacts from extreme weather events (such as storms or heat waves) or from slow-onset hazards (such as sea level rise) (see Ch. 12: Indigenous Peoples).

For example, New Orleans has, through a collection of private and public initiatives, rebuilt some of the neighborhoods damaged by Hurricane Katrina with housing elevated six feet or even higher above the ground and with roofs specially designed to facilitate evacuation.[36] San Francisco has produced a land-use plan to reduce impacts from a rising San Francisco Bay.[37] A similar concern has prompted collective action in four Miami-area counties and an array of San Diego jurisdictions, to name just two locales, to shape future land uses to comply with regulations linked to sea level rise projections.[36,38] Chicago has produced a plan for limiting the number of casualties, especially among the elderly and homeless, during heat waves (Ch. 9: Human Health).[36] Deeper discussion of the factors commonly influencing adaptation decisions at household, municipal, state, and federal levels is provided in Chapter 28 (Ch. 28: Adaptation) of this report; Chapters 26 (Ch. 26: Decision Support) and 27 (Ch. 27: Mitigation) treat the related topics of Decision Support and Mitigation, respectively.

Key Message 4: Reducing Greenhouse Gas Levels

Choices about land use and land management may provide a means of reducing atmospheric greenhouse gas levels.

Choices about land use and land management affect the amount of greenhouse gases entering and leaving the atmosphere and, therefore, provide opportunities to reduce climate change (Ch. 15: Biogeochemical Cycles; Ch. 27: Mitigation).[39] Such choices can affect the balance of these gases directly, through decisions to preserve or restore carbon in standing vegetation (like forests) and soils, and indirectly, in the form of land-use policies that affect fossil fuel emissions by influencing energy consumption for transportation and in buildings. Additionally, as crops are increasingly used to make fuel, the potential for reducing net carbon emissions through replacement of fossil fuels represents a possible land-based carbon emissions reduction strategy, albeit one that is complicated by many natural and economic interactions that will determine the ultimate effect of these strategies on emissions (Ch. 7: Forests; Ch. 6: Agriculture).

Land-cover change and management accounts for about one-third of all carbon released into the atmosphere by people globally since 1850. The primary source related to land use has been the conversion of native vegetation like forests and grasslands to croplands, which in turn has released carbon from vegetation and soil into the atmosphere as carbon dioxide (CO_2).[40] Currently, an estimated 16% of CO_2 going into the atmosphere is due to land-related activities globally, with the remainder coming from fossil fuel burning and cement manufacturing.[40] In the United States, activities related to land use are effectively balanced with respect to CO_2: as much CO_2 is released to the atmosphere by land-use activities as is taken up by and stored in, for example, vegetation and soil. The regrowth of forests and increases of conservation-related forest and crop management practices have also increased carbon storage. Overall, setting aside emissions due to burning fossil fuels, in the U.S. and the rest of North America, land cover takes up more carbon than it releases. This has happened as a result of more efficient forest and agricultural management practices, but it is not clear if this rate of uptake can be increased or if it will persist into the future. The projected declines in forest area (Figure 13.3) put these carbon stores at risk. Additionally, the rate of carbon uptake on a given acre of forest can vary with weather, making it potentially sensitive to climate changes.[41]

Opportunities to increase the net uptake of carbon from the atmosphere by the land include[42] increasing the amount of area in ecosystems with high carbon content (by converting farms to forests or grasslands); increasing the rate of carbon uptake in existing ecosystems (through fertilization); and reducing carbon loss from existing ecosystems (for example, through no-till farming).[43] Because of these effects, policies specifically aimed at increasing carbon storage, either directly through mandates or indirectly through a market for carbon offsets, may be used to encourage more land-based carbon storage.[44]

The following uncertainties deserve further investigation: 1) the effects of these policies or actions on the balance of other greenhouse gases, like methane and nitrous oxide; 2) the degree of permanence these carbon stores will have in a changing climate (especially through the effects of disturbances like fires and plant pests[45]); 3) the degree to which increases in carbon storage can be attributed to any specific policy, or whether or not they may have occurred without any policy change; and 4) the possibility that increased carbon storage in one location might be partially offset by releases in another. All of these specific mitigation options present implementation challenges, as the decisions must be weighed against competing objectives. For example, retiring farmland to sequester carbon may be difficult to achieve if crop prices rise,[46] such as has occurred in recent years in response to the fast-growing market for biofuels. Agricultural research and development that increases the productivity of the sector presents the possibility of reducing demand for agricultural land and may serve as a powerful greenhouse gas mitigation strategy, although the ultimate net effect on greenhouse gas emissions is uncertain.[47]

Land-use decisions in urban areas also present carbon reduction options. Carbon storage in urban areas can reach densities as high as those found in tropical forests, with most of that carbon found in soils, but also in vegetation, landfills, and the structures and contents of buildings.[48] Urban and suburban areas tend to be net sources of carbon to the atmosphere, whereas exurban and rural areas tend to be net sinks.[49] Effects of urban development patterns on carbon storage and emissions due to land and fossil fuel use are topics of current research and can be affected by land-use planning choices. Many cities have adopted land-use plans with explicit carbon goals, typically targeted at reducing carbon emissions from the often intertwined activities of transportation and energy use. This trend, which includes major cities such as Los Angeles,[50] Chicago,[51] and New York City[52] as well as small towns, such as Homer, Alaska,[53] has occurred even in the absence of a formal federal climate policy.

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:
The author team benefited from a number of relevant technical input reports. One report described the findings of a three-day workshop held from November 29 to December 1, 2011, in Salt Lake City, in which a number of the chapter authors participated.2 Findings of the workshop provided a review of current issues and topics as well as the availability and quality of relevant data. In addition, from December 2011 through June 2012 the author team held biweekly teleconferences. Key messages were identified during this period and discussed in two phases, associated with major chapter drafts. An early draft identified a number of issues and key messages. Based on discussions with National Climate Assessment (NCA) leadership and other chapter authors, the Land Use and Land Cover Change authors identified and reached consensus on a final set of four key messages and organized most of the chapter to directly address these messages. The authors selected key messages based on the consequences and likelihood of impacts, the implied vulnerability, and available evidence. Relevance to decision support, mitigation, and adaptation was also an important criterion for the selection of key messages for the cross-cutting and foundational topic of this chapter.

The U.S. acquires, produces, and distributes substantial data that characterize the nation's land cover and land use. Satellite observations, with near complete coverage over the landscape and consistency for estimating change and trends, are particularly valuable. Field inventories, especially of agriculture and forestry, provide very reliable data products that describe land cover as well as land-use change. Together, remote sensing and field inventory data, as well as related ecological and socioeconomic data, allow many conclusions about land-use and land-cover change with very high confidence.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Choices about land-use and land-cover patterns have affected and will continue to affect how vulnerable or resilient human communities and ecosystems are to the effects of climate change.

Description of evidence base
The influences of climate on vegetation and soils, and thus on land cover and land use, are relatively well understood, and a number of well-validated mathematical models are used to investigate potential consequences of climate change for ecosystem processes, structure, and function. Given scenarios about socioeconomic factors or relevant models, some aspects of land-use and land-cover change can also be analyzed and projected into the future based on assumed climate change. During a workshop convened to review land-use and land-cover change for the NCA, participants summarized various studies from different perspectives, including agriculture and forestry as well as socioeconomic issues such as flood insurance.[2]

Residential exposure to wildfire is an excellent example supporting this key message and is well documented in the literature.[16,17,18]

New information and remaining uncertainties
Steadily accumulating field and remote sensing observations as well as inventories continue to increase confidence in this key message. A recent study by the EPA[13] provides relevant projections of housing density and impervious surface under alternative scenarios of climate change.

While there is little uncertainty about the general applicability of this key message, the actual character and consequences of climate change as well as its interactions with land cover and land use vary significantly between locations and circumstances. Thus the specific vulnerabilities resulting from the specific ways in which people, both as individuals and as collectives, will respond to anticipated or observed climate change impacts are less well understood than the biophysical dimensions of this problem.

Assessment of confidence based on evidence
Very High. Observed weather and climate impacts and consequences for land cover and land use, basic understanding of processes and analyses using models of those processes, as well as substantial literature are consistent in supporting this key message.

KEY MESSAGE#2 TRACEABLE ACCOUNT

Land-use and land-cover changes affect local, regional, and global climate processes.

Description of evidence base

The dependence of weather and climate processes on land surface properties is reasonably well understood in terms of the biophysical processes involved. Most climate models represent land-surface conditions and processes, though only recently have they begun to incorporate these conditions dynamically to represent changes in the land surface within a model run. Regional weather models are increasingly incorporating land surface characteristics. Extensive literature – as well as textbooks – documents this understanding, as do models of land surface processes and properties. A Technical Input report to the National Climate Assessment[1] summarizes the literature and basic understanding of interactions between the atmosphere and land surface that influence climate.

Examples are provided within the chapter to demonstrate that land-use and land-cover change are affecting U.S. climate.[20,24,25,27,31,32,33,34]

New information and remaining uncertainties

While there is little uncertainty about this key message in general, the heterogeneity of the U.S. landscape and associated processes, as well as regional and local variations in atmospheric processes, make it difficult to analyze or predict the character of land use and land cover influences on atmospheric processes at all scales.

Assessment of confidence based on evidence

Very High. The basic processes underlying the biophysics of interactions between the land surface and atmosphere are well understood. A number of examples and field studies are consistent in demonstrating effects of land use and land-cover change on the climate of the United States.

Key message #3 Traceable Account

Individuals, businesses, non-profits, and governments have the capacity to make land-use decisions to adapt to the effects of climate change.

Description of evidence base

The key message is supported by well-understood aspects of land-use planning and management, including the legal roles of government and citizens and management practices such as zoning and taxation. Participants in the NCA workshop (Nov 29-Dec 1, 2011, in Salt Lake City) on land use and land cover presented and discussed a number of examples showing the influences of land-use decisions on climate change adaptation options.[2] The chapter describes specific examples of measures to adapt to climate change, further supporting this key message.[36,37,38]

New information and remaining uncertainties

Experience with climate change adaptation measures involving land-use decisions is accumulating rapidly.[36,37,38] Although there is little uncertainty that land-use decisions can enable adaptation to climate change, the information about climate change, at scales where such decisions are made, is generally lacking.

Assessment of confidence based on evidence

Very High. The aspects of land-use planning that can enable climate change adaptation are well understood and examples demonstrate where actions are being taken.

Key message #4 Traceable Account

Choices about land use and land management provide a means of reducing atmospheric greenhouse gas levels.

Description of evidence base

The evidence base for this key message includes scientific studies on the carbon cycle at both global and local scales (summarized in Izzauralde et al. 2013; Hurteau 2013; and Cambardella and Hatfield 2013).[42,43,45] The evidence base also includes policy studies on the costs and benefits and feasibilities of various actions to reduce carbon emissions from land-based activities and/or to increase carbon storage in the biosphere through land-based activities (summarized in Jones et al. 2013; and Pearson and Brown 2013).[44] Foundational studies are summarized in the NCA Technical Input documents.[1,2]

New information and remaining uncertainties

A major study by the U.S. Geological Survey is estimating carbon stocks in vegetation and soils of the U.S., and this inventory will

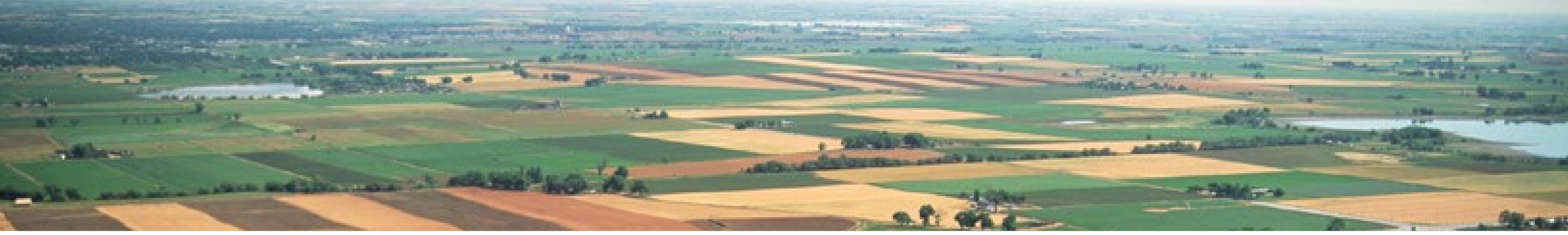
Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

clarify the potential for capturing greenhouse gasses by land-use change (an early result is reported in Sohl et al. 2012[14]).

There is little uncertainty behind the premise that specific land uses affect the carbon cycle. There are, however, scientific uncertainties regarding the magnitudes of effects resulting from specific actions designed to leverage this linkage for mitigation. For example, uncertainties are introduced regarding the permanence of specific land-based stores of carbon, the incremental value of specific management or policy decisions to increase terrestrial carbon stocks beyond changes that would have occurred in the absence of management, and the possibility for decreases in carbon storage in another location that offset increases resulting from specific actions at a given location. Also, we do not yet know how natural processes might alter the amount of carbon storage expected to occur with management actions. There are further uncertainties regarding the political feasibilities and economic efficacy of policy options to use land-based activities to reduce the concentration of greenhouse gases in the atmosphere.

Assessment of confidence based on evidence

Given the evidence base and uncertainties, there is **medium** confidence that land use and land management choices can reduce the amount of greenhouse gases in the atmosphere.



Climate Change Impacts in the United States

CHAPTER 14
RURAL COMMUNITIES

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On the Web: http://nca2014.globalchange.gov/report/sectors/rural-communities

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

14 RURAL COMMUNITIES

KEY MESSAGES

1. **Rural communities are highly dependent upon natural resources for their livelihoods and social structures. Climate change related impacts are currently affecting rural communities. These impacts will progressively increase over this century and will shift the locations where rural economic activities (like agriculture, forestry, and recreation) can thrive.**
2. **Rural communities face particular geographic and demographic obstacles in responding to and preparing for climate change risks. In particular, physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increase the vulnerability of rural communities. Systems of fundamental importance to rural populations are already stressed by remoteness and limited access.**
3. **Responding to additional challenges from climate change impacts will require significant adaptation within rural transportation and infrastructure systems, as well as health and emergency response systems. Governments in rural communities have limited institutional capacity to respond to, plan for, and anticipate climate change impacts.**

More than 95% of U.S. land area is classified as rural, but is home to just 19% of the population (see also Ch. 13: Land Use & Land Cover Change).[1] Rural America's importance to the country's economic and social well-being is disproportionate to its population, as rural areas provide natural resources that much of the rest of the United States depends on for food, energy, water, forests, recreation, national character, and quality of life.[2] Rural economic foundations and community cohesion are intricately linked to these natural systems, which are inherently vulnerable to climate change. Urban areas that depend on goods and services from rural areas will also be affected by climate change driven impacts across the countryside.

Warming trends, climate volatility, extreme weather events, and environmental change are already affecting the economies and cultures of rural areas. Many rural communities face considerable risk to their infrastructure, livelihoods, and quality of life from observed and projected climate shifts (Ch. 12: Indigenous Peoples). These changes will progressively increase volatility in food commodity markets, shift the ranges of plant and animal species, and, depending on the region, increase water scarcity, exacerbate flooding and coastal erosion, and increase the intensity and frequency of wildfires across the rural landscape.

Climate changes will severely challenge many rural communities, shifting locations where particular economic activities are capable of thriving. Changes in the timing of seasons, temperatures, and precipitation will alter where commodities, value-added crops, and recreational activities are best suited. Because many rural communities are less diverse than urban areas in their economic activities, changes in the viability of one traditional economic sector will place disproportionate stresses on community stability.

Climate change impacts will not be uniform or consistent across rural areas, and some communities may benefit from climate change. In the short term, the U.S. agricultural system is expected to be fairly resilient to climate change due to the system's flexibility to engage in adaptive behaviors such as expansion of irrigated acreage, regional shifts in acreage for specific crops, crop rotations, changes to management decisions (such as choice and timing of inputs and cultivation practices), and altered trade patterns compensating for yield changes (Ch.


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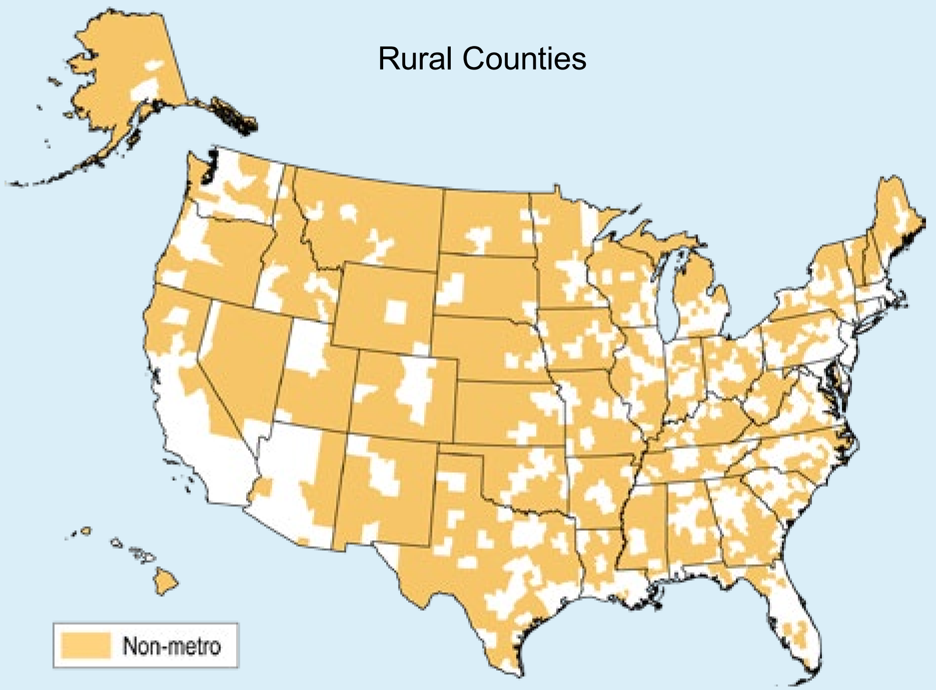

Figure 14.1. Although the majority of the U.S. population lives in urban areas, most of the country is still classified as rural. In this map, counties are classified as rural if they do not include any cities with populations of 50,000 or more. (Figure source: USDA Economic Research Service 2013[3]).

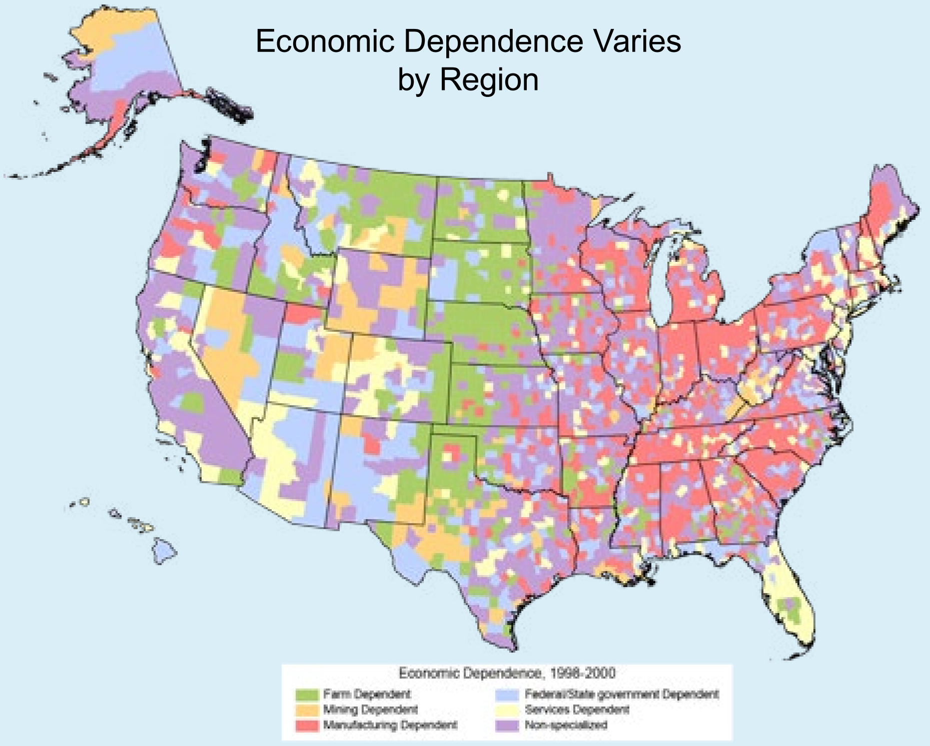

Figure 14.2. Much of the rural United States depends on agriculture, mining, and manufacturing. Climate changes will affect each region and each economic sector in complex and interrelated ways. The economic dependence classification used in the map indicates the largest share of earnings and employment in each county. (Figure source: USDA Economic Research Service 2013[3]).

6: Agriculture; Key Message 5).[4] Recreation, tourism, and leisure activities in some regions will benefit from shifts in temperature and precipitation.

Negative impacts from projected climate changes, however, will ripple throughout rural America. Agricultural systems in some areas may need to undergo more transformative changes to keep pace with future climate change (Ch. 6: Agriculture, Key Message 5). In lakes and riparian areas, warming is projected to increase the growth of algae and invasive species, particularly in areas already facing water quality impairments.[5] Mountain species and cold water fish, such as salmon, are expected to face decreasing range sizes due to warming, while ranges could expand for some warm water fish, such as bass.[6] Alaska, with its reliance on commercial and subsistence fishing catch, is particularly vulnerable. Warmer weather and higher water temperatures will reduce salmon harvests, creating hardships for the rural communities and tribes that depend upon these catches (Ch. 12: Indigenous Peoples, Key Message 1).[7] Communities in Guam and American Samoa, which depend on fish for 25% to 69% of their protein, are expected to be particularly hard hit as climate change alters the composition of coral reef ecosystems.[8]

Across the United States, rural areas provide ecosystem services – like carbon absorption in forests, water filtration in wetlands, wildlife habitat in prairies, and environmental flows in rivers and streams – whose value tends to be overlooked. Preserving these ecosystem services sustains the quality of life in rural communities and also benefits those who come to rural communities for second homes, tourism, and other amenities. They also provide urban residents with vital resources – like food, energy, and fresh water – that meet essential needs. This layered connection between rural areas and populous urban centers suggests that maintaining the health of rural areas is a national, and not simply a local, concern.

Key Message 1: Rural Economies

Rural communities are highly dependent upon natural resources for their livelihoods and social structures. Climate change related impacts are currently affecting rural communities. These impacts will progressively increase over this century and will shift the locations where rural economic activities (like agriculture, forestry, and recreation) can thrive.

Rural America has already experienced some of the impacts of climate change related weather effects, including crop and livestock loss from severe drought and flooding,[9] infrastructure damage to levees and roads from extreme storms,[10] shifts in planting and harvesting times in farming communities,[11] and large-scale losses from fires and other weather-related disasters.[12] These impacts have profound effects, often significantly affecting the health and well-being of rural residents as well as their communities, and are amplified by the essential economic link that many of these communities have to their natural resource base.

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River flood waters illustrate threats rural areas face in a changing climate.

Rural communities are often characterized by their natural resources and associated economic activity. Dominant economic drivers include agriculture, forestry, mining, energy, outdoor recreation, and tourism. In addition, many rural areas with pleasant climates and appealing landscapes are increasingly reliant on second-home owners and retirees for their tax base and community activities.

Nationally, fewer than 7% of rural workers are directly employed in agriculture, but the nation's two million farms occupy more than 40% of U.S. land mass – and many rural

Growing Season Lengthens

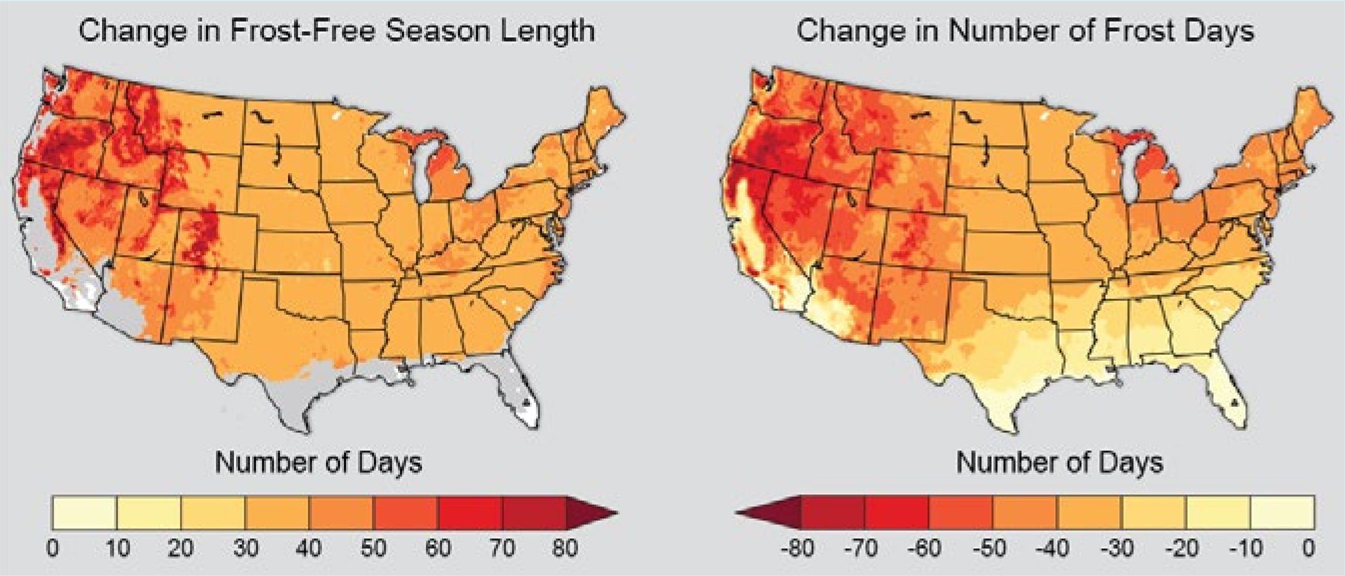

Figure 14.3. The left map shows that if emissions continue to increase (A2 scenario), the U.S. growing season (or frost-free season) will lengthen by as much as 30 to 80 days by the end of the century (2070-2099 as compared to 1971-2000). The right map shows a reduction in the number of frost days (days with minimum temperatures below freezing) by 20 to 80 days in much of the United States in the same time period. While changes in the growing season may have positive effects for some crops, reductions in the number of frost days can result in early bud-bursts or blooms, consequently damaging some perennial crops grown in the United States (See also Ch. 6: Agriculture). White areas are projected to experience no freezes for 2070-2099, and gray areas are projected to experience more than 10 freeze-free years during the same period. (Figure source: NOAA NCDC / CICS-NC).

communities rely extensively on farming and ranching (Ch. 6 Agriculture; Ch. 13 Land Use & Land Cover Change).[13] Farmers are responding to climate change by shifting cropping patterns and altering the timing of planting and harvesting. This may result in additional use of herbicides and pesticides with the accompanying human exposure to additional health risks.[14] Changes in rainfall, temperature, and extreme weather events will increase the risk of poor yields and reduced crop profitability. For example, the increased frequency and intensity of heavy downpours will accelerate soil erosion rates, increasing deposition of nitrogen and phosphorous into water bodies and diminishing water quality.[15]

Many areas will face increasing competition for water among household, industrial, agricultural, and urban users (Ch. 3: Water).[16] Reduced surface water will place more stress on surface water systems as well as groundwater systems (Ch. 3: Water; Key Message 4). In-stream flow requirements for the maintenance of environmental resources are an equally important water demand. While irrigated cropland is an important and growing component of the farm economy,[17] water withdrawals necessary for generating electricity in thermal power plants are already roughly equal to irrigation withdrawals.[18] As climate change increases water scarcity in some regions, there will be increased competition for water between energy production and agriculture.[19] Mining also requires large quantities of water, and scarcity resulting from drought associated with climate change may affect operations. Changes in seasonality and intensity of precipitation will increase costs of runoff containment. Climate change impacts on forestry have important implications for timber and forest-amenity-based rural communities. Shifting forest range and composition, as well as increased attacks from pests and diseases, will have negative effects on biodiversity and will increase wildfire risks (Ch. 7: Forests).[8,20] Shifts in the distribution and abundance of many economically important tree species would affect the pulp and wood industry. As ranges shift and the distribution of plant species in forests changes, the range of other forest-dependent animal species will also change, causing additional economic and sociocultural impacts.

Tourism contributes significantly to rural economies. Changes in the length and timing of seasons, temperature, precipitation, and severe weather events can have a direct impact on tourism and recreation activities by influencing visitation patterns and tourism-related economic activity.

Climate change impacts on tourism and recreation will vary significantly by region. For instance, some of Florida's top tourist attractions, including the Everglades and Florida Keys, are threatened by sea level rise,[21] with estimated revenue losses of $9 billion by 2025 and $40 billion by the 2050s. The effects of climate change on the tourism industry will not be exclusively negative. In Maine, coastal tourism could increase due to warmer summer months, with more people visiting the state's beaches.[22] Employing a Tourism Climatic Index (Figure 14.4) that accounts for temperature, precipitation, sunshine, and wind, one study finds that conditions conducive for outdoor recreation will be shifting northward with climate change, though it is unclear whether absolute conditions or relative weather conditions will be more important in influencing future tourist behaviors.[23]

Climate Change Impacts on Summertime Tourism

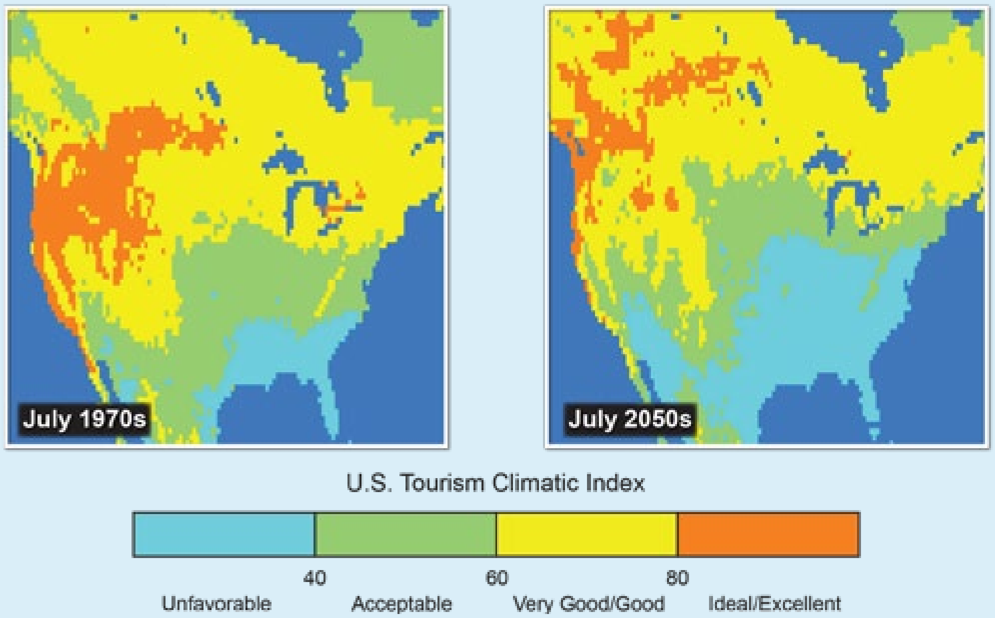

Figure 14.4. Tourism is often climate-dependent as well as seasonally dependent. Increasing heat and humidity – projected for summers in the Midwest, Southeast, and parts of the Southwest by mid-century (compared to the period 1961-1990) – is likely to create unfavorable conditions for summertime outdoor recreation and tourism activity. The figures illustrate projected changes in climatic attractiveness (based on maximum daily temperature and minimum daily relative humidity, average daily temperature and relative humidity, precipitation, sunshine, and wind speed) in July for much of North America. In the coming century, the distribution of these conditions is projected to shift from acceptable to unfavorable across most of the southern Midwest and a portion of the Southeast, and from very good or good to acceptable conditions in northern portions of the Midwest, under a high emissions scenario (A2a). (Figure source: Nicholls et al. 2005[24]).

Climate change will also influence the distribution and composition of plants and animals across the United States. Hunting, fishing, bird watching, and other wildlife-related activities will be affected as habitats shift and relationships among species change.[25] Cold-weather recreation and tourism will be adversely affected by climate change. Snow accumulation in the western United States has decreased, and is expected to continue to decrease, as a result of observed and projected warming. Reduced snow accumulation also reduces the amount of spring snowmelt, decreasing warm-season runoff in mid- to high-latitude regions.

Similar changes to snowpack are expected in the Northeast.[26] Adverse impacts on winter sports are projected to be more pronounced in the Northeast and Southwest regions of the United States.[8] Coastal areas will be adversely affected by sea level rise and increased severity of storms.[22,27] Changing environmental conditions, such as wetland loss and beach erosion in coastal areas[28] and increased risk of natural hazards such as wildfire, flash flooding, storm surge, river flooding, drought, and extremely high temperatures can alter the character and attraction of rural areas as tourist destinations.

The implications of climate change on communities that are dependent on resource extraction (coal, oil, natural gas, and mining) have not been well studied. Attributes of economic development in these communities, such as cyclical growth, transient workforce, rapid development, pressure on infrastructure, and lack of economic diversification suggest that these communities could face challenges in adapting to climate change.[13,29,30]

Key Message 2: Responding to Risks

Rural communities face particular geographic and demographic obstacles in responding to and preparing for climate change risks. In particular, physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increase the vulnerability of rural communities. Systems of fundamental importance to rural populations are already stressed by remoteness and limited access.

Relatively rapid changes in demographics, economic activity, and climate are particularly challenging in rural communities, where local, agrarian values often run generations deep. Changing rural demographics, influenced by new immigration patterns, fluctuating economic conditions, and evolving community values add to these challenges – especially with regard to climate changes.

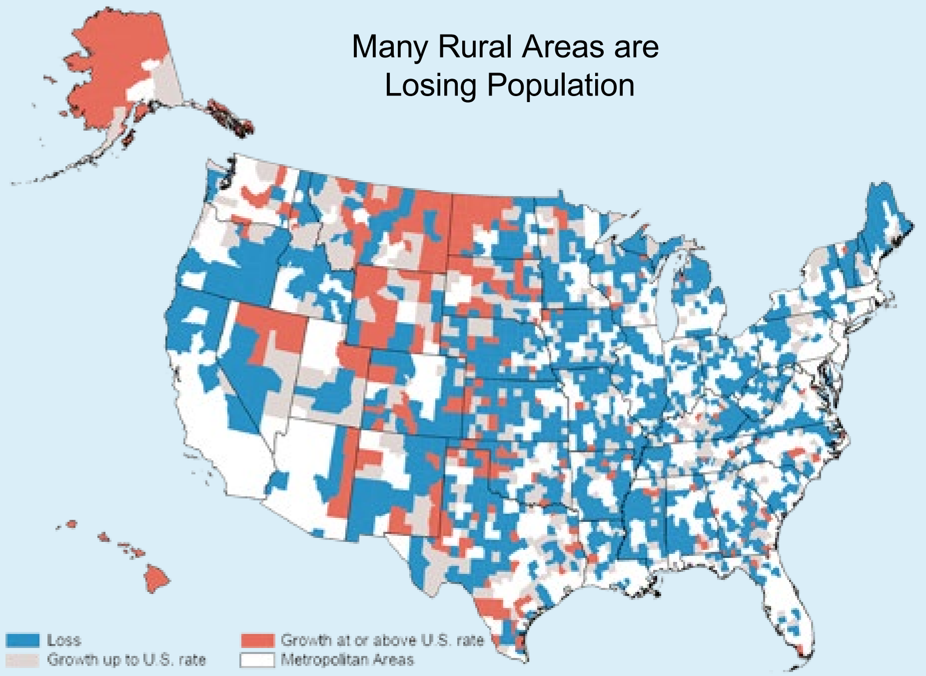

Figure 14.5. Census data show significant population decreases in many rural areas, notably in the Great Plains. Many rural communities' existing vulnerabilities to climate change, including physical isolation, reduced services like health care, and an aging population, are projected to increase as population decreases. (Figure source: USDA Economic Research Service 2013[3]).

Modern rural populations are generally older, less affluent, and less educated than their urban counterparts. Rural areas are characterized by higher unemployment, more dependence on government transfer payments, less diversified economies, and fewer social and economic resources needed for resilience in the face of major changes.[8,31] In particular, the combination of an aging population and poverty increases the vulnerability of rural communities to climate fluctuations.

There has been a trend away from manufacturing, resource extraction, and farming to amenity-based economic activity in many rural areas of the United States.[32] Expanding amenity-based economic activities in rural areas include recreation and leisure, e-commuting residents, tourism, and second home and retirement home development. This shift has stressed traditional cultural values[33] and put pressure on infrastructure[34] and natural amenities[35] that draw people to rural areas. Changes in climate and weather are likely to increase these stresses. Rural components of transportation systems are particularly vulnerable to risks from flooding and sea level rise.[36] Since rural areas often have fewer transportation options and fewer infrastructure redundancies, any disruptions in road, rail, or air transport will deeply affect rural communities.

Power and communication outages resulting from extreme events often take longer to repair in rural areas, contributing to the isolation and vulnerability of elderly residents who may not have cell phones. The lack of cellular coverage in some rural areas can create problems for emergency response during power failures.[37]

In some parts of the country there has been a recent trend in Hispanic population growth in rural regions that have not been traditional migrant destinations. New Hispanic immigrants are often highly segregated residentially and isolated from mainstream institutions,[38] making them more vulnerable to changes in climate. Low wages, unstable work, language barriers, and inadequate housing are critical obstacles to managing climate risk.

Rural communities rely on various transportation modes, both for export and import of critical goods (Ch. 5: Transportation). Climate changes will result in increased erosion and maintenance costs for local road and rail systems, as well as changes in streamflows and predictability that will result in increased maintenance costs for waterways. More frequent disruption of shipping is projected, with serious economic consequences. For example, in 2010, about 40 million tons of cereal grains were shipped by water to Louisiana, while less than 4 million tons traveled by rail.[10] While rail can help ameliorate small-scale or off-peak capacity limitations on the Mississippi River, it seems unlikely that the rail system can fully replace the river system in the event of a prolonged harvest-time disruption. Events that affect both rail and barge traffic would be particularly damaging to rural communities that depend upon these systems to get commodities to market.

Health and emergency response systems also face additional demands from substantial direct and indirect health risks associated with global climate changes. Indirect risks, particularly those posed by emerging and reemerging infectious diseases, are more difficult to assess, but pose looming threats to economically challenged communities where health services are limited. Direct threats (such as extreme heat, storm events, and coastal and riparian flooding) tend to be more associated with specific local vulnerabilities, so the risks are somewhat easier to assess.[39]

The socioeconomic and demographic characteristics of rural areas interact with climate change to create health concerns that differ from those of urban and suburban communities. Older populations with lower income and educational levels in rural areas spend a larger proportion of their income on health care than their urban counterparts. Moreover, health care access declines as geographic isolation increases. Overall, rural residents already have higher rates of age-adjusted mortality, disability, and chronic disease than do urban populations.[40] These trends are likely to be exacerbated by climate change (Ch. 9: Human Health).

Governments in rural areas are generally ill-prepared to respond quickly and effectively to large-scale events, although individuals and voluntary associations often show significant resilience. Health risks are exacerbated by limitations in the health service systems characteristic of rural areas, including the distance between rural residents and health care providers and the reduced availability of medical specialists.

The effects of climate change on mental health merit special consideration. Rural residents are already at a heightened risk from mental health issues because of the lack of access to mental health providers. The adverse impact of severe weather disasters on mental health is well established,[41] and there is emerging evidence that climate change in the form of increasing heat waves and droughts has harmful effects on mental health (Ch. 9: Human Health, Key Message 1). Droughts often result in people relocating to seek other employment, causing a loss of home and social networks. Studies have shown that springtime droughts in rural areas cause a decrease in life satisfaction.[42] The primary care physicians who form the backbone of rural health care often have heavy caseloads and lack specialized training in mental health issues.[40] Additionally, patients referred to mental health specialists often experience significant delays.[43]

The frequency and distribution of infectious diseases is also projected to increase with rising temperatures and associated seasonal shifts. Increased rates of mutation and increased resistance to drugs and other treatments are already evident in the behavior of infectious disease-causing bacteria and viruses.[44] In addition, changes in temperature, surface water, humidity, and precipitation affect the distribution and abundance of disease-carriers and intermediate hosts, and result in larger distributions for many parasites and diseases. Rural residents who spend significant time outdoors have an increased risk of exposure to these disease-carriers, like ticks and mosquitoes (Ch. 9: Human Health).

Key Message 3: Adaptation

Responding to additional challenges from climate change impacts will require significant adaptation within rural transportation and infrastructure systems, as well as health and emergency response systems. Governments in rural communities have limited institutional capacity to respond to, plan for, and anticipate climate change impacts.

Climate variability and increases in temperature, extreme events (such as storms, floods, heat waves, and droughts), and sea level rise are expected to have widespread impacts on the provision of services from state, regional, local, and tribal governments. Emergency management, energy use and distribution systems, transportation and infrastructure planning, and public health will all be affected.

Rural governments often depend heavily on volunteers to meet community challenges like fire protection or flood response. In addition, rural communities have limited locally available financial resources to help deal with the effects of climate change. Small community size tends to make services expensive or available only by traveling some distance.

Local governance structures tend to de-emphasize planning capacity, compared to urban areas. While 73% of metropolitan counties have land-use planners, only 29% of rural counties not adjacent to a metropolitan county had one or more planners. Moreover, rural communities are not equipped to deal with major infrastructure expenses.[45]

Communities across the United States are experiencing infrastructure losses, water scarcity, unpredictable water availability, and increased frequency and intensity of wildfires. However, local authorities often do not explicitly associate these observed changes with climate, and responses rarely take climate disruption into account. Even in communities where there is increasing awareness of climate change and interest in comprehensive adaptation planning, lack of funding, human resources, access to information, training, and expertise provide significant barriers for many rural communities.[46]

If rural communities are to respond adequately to future climate changes, they will likely need help assessing their risks and vulnerabilities, prioritizing and coordinating projects, funding and allocating financial and human resources, and deploying information-sharing and decision support tools (Ch. 26: Decision Support). There is still little systematic research on the vulnerability of rural communities and there is a need for additional empirical research in this area. Impacts due to climate change will cross community and regional lines, making solutions dependent upon meaningful participation of numerous stakeholders from federal, state, local, and tribal governments, science and academia, the private sector, non-profit organizations, and the general public (Ch. 28: Adaptation, Key Message 3).

Effective adaptation measures are closely tied to specific local conditions and needs and take into account existing social networks.[47,48] The economic and social diversity of rural communities affects the ability of both individuals and communities to adapt to climate changes, and underscores the need to assess climate change impacts on a local basis. The quality and availability of natural resources, legacies of past use, and changing industrial needs affect the economic, environmental, and social conditions of rural places and are critical factors to be assessed.[13,30,49] Successful adaptation to climate change requires balancing immediate needs with long-term development goals, as well as development of local-level capacities to deal with climate change.[48,50]

Potential national climate change mitigation responses (Ch. 27: Mitigation) – especially those that require extensive use of land, such as permanent reforestation, constructing large solar or wind arrays, hydroelectric generation, and biofuel cropping – are also likely to significantly affect rural communities, with both positive and negative effects.[51] As with the development of rural resource-intensive economic activities, where national or multi-national companies tend to wield ownership and control, local residents and communities are unlikely to be the primary investors in or beneficiaries of this kind of new economic activity. For example, mitigation policies that affect coal production could have a substantial economic impact on many rural communities, as could policies to promote production of non-fossil-fuel energy such as wind.

Decisions regarding adaptation responses for both urban and rural populations can occur at various scales (federal, state, local, tribal, private sector, and individual) but need to take interdependencies into account. Many decisions that significantly affect rural communities may not be under the control of local governments or rural residents. Given that timing is a critical aspect of adaptation, as well as mitigation, engaging rural residents early in decision processes about investments in public infrastructure, protection of shorelines, changes in insurance provision, or new management initiatives can influence individual behavior and choice in ways that enhance positive outcomes of adaptation and mitigation.

LOCAL RESPONSES TO CLIMATE CHANGE IN THE SAN JUAN MOUNTAINS

The San Juan Mountains region straddles the southern edge of the Southern Rocky Mountains and the northeastern tip of the arid Southwest. The high mountain headwaters of the Rio Grande, San Juan, and major tributaries of the Upper Colorado River are critical water towers for five states: Texas, Nevada, California, Arizona, and New Mexico. The diversity of the landforms, high plateaus, steep mountains, deep canyons, and foothills leads to a complex and diverse mix of coniferous and deciduous forested landscapes.[52] County populations in the area range from 700 to 51,000 people. Population changes between 2000 and 2010 ranged from a 25% decline to an 86% increase. Public lands account for 69% of the land base.[53] Over half of the local economies are dependent upon natural resources to support tourism, minerals and natural gas extraction, and second home development.

Average annual temperatures in the San Juan Mountains have risen 1.1°F in only three decades,[54] a rate of warming greater than any other region of the United States except Alaska.[55] The timing of snowmelt has shifted two weeks earlier between 1978 and 2007, and this earlier seasonal release of water resources is of particular concern to all western states.[56] Current challenges for the region include changes in forests due to pests and diseases, intensive recreation use, fire management for natural and prescribed fires, and increasing development in the wildland-urban interface. Communities are vulnerable to changes from a warmer and drier climate that would affect the frequency and intensity of wildfires, shift vegetation and range of forest types, and increase pressures on water supplies.

In response, the San Juan Climate Initiative drew together stakeholders, including natural resource managers, community planners, elected officials, industry representatives, resource users, citizens, non-profit organizations, and scientists. By combining resources and capabilities, stakeholders have been able to accomplish much more together than if they had worked independently. For example, local governments developed a plan to reduce greenhouse gas emissions and identify strategies for adaptation, signing the U.S. Mayor's Climate Protection Agreement in 2009. Climate modelers at University of Colorado and National Center for Atmospheric Research analyzed regional trends in temperature, precipitation, snowpack, and streamflow. Researchers at Mountain Studies Institute, University of Colorado, and Fort Lewis College are partnering with San Juan National Forest to monitor alpine plant communities and changes in climate across the region, and to document carbon resources. San Juan National Forest is developing strategies for adapting to climate changes in the region related to drought, wildfire, and other potential effects. La Plata County is leading an effort to plan for sustainable transportation and food networks that will be less dependent upon carbon-based fuels, while the Mountain Studies Institute is leading citizen science programs to monitor changes to sensitive species like the American pika.

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Hiker in the San Juan mountains, Colorado.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Message:
The key messages were initially developed at a meeting of the authors in Charleston, South Carolina, in February 2012. This initial discussion was supported by a series of conference calls from March through June, 2012. These ensuing discussions were held after a thorough review of the technical inputs and associated literature, including the Rural Communities Workshop Report prepared for the NCA[57] and additional technical inputs on a variety of topics.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Rural communities are highly dependent upon natural resources for their livelihoods and social structures. Climate change related impacts are currently affecting rural communities. These impacts will progressively increase over this century and will shift the locations where rural economic activities (like agriculture, forestry, and recreation) can thrive.

Description of evidence base
The key message and supporting text summarizes extensive evidence documented in the Rural Communities Workshop Report.[57] Thirty one technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that the impacts of climate change are increasing is compelling and widespread. This evidence is based on historical records and observations and on global climate models, including those driven by B1 (substantial emissions reduction) and A2 (continued increases in global emissions) scenarios. This evidence is clearly summarized and persuasively referenced in the "Our Changing Climate" chapter of this Assessment and in the Scenarios developed for the NCA.[58]

The dependency of rural communities on their natural resources has been demonstrated,[13] with a number of studies showing that climate change results in crop and livestock loss,[9] infrastructure damage to levees and roads,[10] shifts in agriculture practices,[11] and losses due to disasters.[12] A number of publications project these impacts to increase, with effects on the natural environment[8,15,20] and increased competition for water between agriculture and energy.[19] Studies have projected that tourism locations in the Everglades and Florida Keys are threatened.[21] Meanwhile, Maine's tourism could increase,[22] which coincides with a projected northern shift in outdoor recreation.[23] Hunting, fishing, and bird watching will be affected by beach erosion and wetland loss,[28] and changing plant and animal habitats and inter-species relationships (see also Ch. 8: Ecosystems). Outdoor recreation and tourism in many areas in the U.S. are affected by early snowpack melt.[8,26]

New information and remaining uncertainties
Key remaining uncertainties relate to the precise magnitude, timing, and location of impacts at regional and local scales.

Assessment of confidence based on evidence
(See confidence level key on next page)

Given the evidence and uncertainties, there is **very high** confidence that rural communities are highly dependent on natural resources that are expected to be affected by climate change, especially the many communities that rely on farming, forestry or tourism for their livelihoods.

Given the evidence and uncertainties, there is **high** confidence that climate change is currently affecting rural communities.

Given the evidence and uncertainties, there is **very high** confidence that impacts will increase (see Ch 2: Our Changing Climate).

Given the evidence and uncertainties, there is **high** confidence about shifts in locations of economic activities.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Rural communities face particular geographic and demographic obstacles in responding to and preparing for climate change risks. In particular, physical isolation, limited economic diversity, and higher poverty rates, combined with an aging population, increase the vulnerability of rural communities. Systems of fundamental importance to rural populations are already stressed by remoteness and limited access.

Description of evidence base

The key message and supporting text summarizes extensive evidence documented in the Rural Communities Workshop Report.[57] Thirty one technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

With studies showing that rural communities are already stressed,[33,34,35] a number of publications have explored the barriers of rural communities to preparing and responding to climate change.[8,31] Some studies provide in-depth looks at the obstacles created by limited economic diversity[32] and an aging population.[40]

New information and remaining uncertainties

Projecting the interactions of these variables with each other and applying this analysis to local or regional realities is complex at best, with uncertainties at every level of analysis.

Assessment of confidence based on evidence

Given the evidence and uncertainties, there is **high** confidence that the obstacle of physical isolation will hamper some communities' ability to adapt or have an adequate response during extreme events.

Given the evidence and uncertainties, there is **high** confidence that the obstacle of limited economic diversity will hinder rural communities' ability to adapt.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Given the evidence and uncertainties, there is **high** confidence that the obstacle of higher poverty rates will significantly increase vulnerability of many communities from adapting properly.

Given the evidence and uncertainties, there is **high** confidence that the obstacle of an aging population will hinder some rural communities and prevent them from having an adequate response.

Given the evidence and uncertainties, there is **high** confidence that fundamental systems in rural communities are already stressed by remoteness and limited access.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Responding to additional challenges from climate change impacts will require significant adaptation within rural transportation and infrastructure systems, as well as health and emergency response systems. Governments in rural communities have limited institutional capacity to respond to, plan for, and anticipate climate change impacts.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Rural Communities Workshop Report.[57] Thirty one technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Rural communities are not equipped to deal with major infrastructure expenses.[45] Work has been performed illustrating the need to tie adaptation measures to specific local conditions and needs and take into account existing social networks.[47,48] Publications have shown that there are a number of critical factors to be assessed, including the quality and availability of natural resources, legacies of past use of resources, and changing industrial needs that affect economic, environmental, and social conditions.[13,30,49] Additionally, studies have expressed the requirement of accounting for both near- and long-term needs for climate change adaptation to be successful.[50]

New information and remaining uncertainties

It is difficult to fully capture the complex interactions of the entire socioeconomic-ecological system within which the effects of climate change will interact, especially in regard to local and regional impacts. Impact assessments and adaptation strategies require improved understanding of capacity and resilience at every level, international to local. The policy context in which individuals and communities will react to climate effects is vague and uncertain. Identification of informational needs alone indicates that adaptation will be expensive.

Assessment of confidence based on evidence

Given the evidence and uncertainties, there is **high** confidence that rural communities have limited capacity to respond to impacts, because of their remoteness, age, lack of diversity, and other reasons described in the text.

Given the evidence and uncertainties, there is **high** confidence that rural communities have limited capacity to plan for impacts, as explained in the text.

Given the evidence and uncertainties, there is **high** confidence that rural communities will have limited capacity to anticipate impacts because of the lack of infrastructure and expertise available in rural communities.

Given the evidence and uncertainties, there is **high** confidence that significant climate change adaptation is needed for transportation in rural communities.

Given the evidence and uncertainties, there is **high** confidence that significant climate change adaptation is needed for health care and emergency response in rural communities, so that rural communities can handle climate change impacts.

Climate Change Impacts in the United States

CHAPTER 15
BIOGEOCHEMICAL CYCLES

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

15 BIOGEOCHEMICAL CYCLES

KEY MESSAGES

1. **Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.**
2. **In total, land in the United States absorbs and stores an amount of carbon equivalent to about 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink. The effect of this carbon storage is to partially offset warming from emissions of CO_2 and other greenhouse gases.**
3. **Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.**

Biogeochemical cycles involve the fluxes of chemical elements among different parts of the Earth: from living to non-living, from atmosphere to land to sea, and from soils to plants. They are called "cycles" because matter is always conserved and because elements move to and from major pools via a variety of two-way fluxes, although some elements are stored in locations or in forms that are differentially accessible to living things. Human activities have mobilized Earth elements and accelerated their cycles – for example, more than doubling the amount of reactive nitrogen that has been added to the biosphere since pre-industrial times.[1,2] Reactive nitrogen is any nitrogen compound that is biologically, chemically, or radiatively active, like nitrous oxide and ammonia, but not nitrogen gas (N_2). Global-scale alterations of biogeochemical cycles are occurring, from human activities both in the U.S. and elsewhere, with impacts and implications now and into the future. Global carbon dioxide emissions are the most significant driver of human-caused climate change. But human-accelerated cycles of other elements, especially nitrogen, phosphorus, and sulfur, also influence climate. These elements can affect climate directly or act as indirect factors that alter the carbon cycle, amplifying or reducing the impacts of climate change.

Climate change is having, and will continue to have, impacts on biogeochemical cycles, which will alter future impacts on climate and affect our capacity to cope with coupled changes in climate, biogeochemistry, and other factors.

Key Message 1: Human-Induced Changes

Human activities have increased atmospheric carbon dioxide by about 40% over pre-industrial levels and more than doubled the amount of nitrogen available to ecosystems. Similar trends have been observed for phosphorus and other elements, and these changes have major consequences for biogeochemical cycles and climate change.

The human mobilization of carbon, nitrogen, and phosphorus from the Earth's crust and atmosphere into the environment has increased 36, 9, and 13 times, respectively, compared to geological sources over pre-industrial times.[3] Fossil fuel burning, land-cover change, cement production, and the extraction and production of fertilizer to support agriculture are major causes of these increases.[4] Carbon dioxide (CO_2) is the most abundant of the heat-trapping greenhouse gases that are increasing due to human activities, and its production dominates atmospheric forcing of global climate change.[5] However, methane (CH_4) and nitrous oxide (N_2O) have higher greenhouse-warming potential per molecule than CO_2, and both are also increasing in the atmosphere. In the U.S. and Europe, sulfur emissions have declined over the past three decades, especially since the mid-1990s, because of efforts to reduce air pollution.[6] Changes in biogeochemical cycles of carbon, nitrogen, phosphorus, and other elements – and the coupling of those cycles – can influence climate. In turn, this can change atmospheric composition in other ways that affect how the planet absorbs and reflects sunlight (for example, by creating small particles known as aerosols that can reflect sunlight).

State of the Carbon Cycle

The U.S. was the world's largest producer of human-caused CO_2 emissions from 1950 until 2007, when it was surpassed by China. U.S. emissions account for approximately 85% of North American emissions of CO_2[7] and 18% of global emissions.[8,9] Ecosystems represent potential "sinks" for CO_2, which are places where carbon can be stored over the short or long term (see "Estimating the U.S. Carbon Sink"). At the continental scale, there has been a large and relatively consistent increase in forest carbon stocks over the last two decades,[10] due to recovery from past forest harvest, net increases in forest area, improved forest management regimes, and faster growth driven by climate or fertilization by CO_2 and nitrogen.[7,11] The largest rates of disturbance and "regrowth sinks" are in southeastern, south central, and Pacific northwestern regions.[11] However, emissions of CO_2 from human activities in the U.S. continue to increase and exceed ecosystem CO_2 uptake by more than three times. As a result, North America remains a net source of CO_2 into the atmosphere[7] by a substantial margin.

Major North American Carbon Dioxide Sources and Sinks

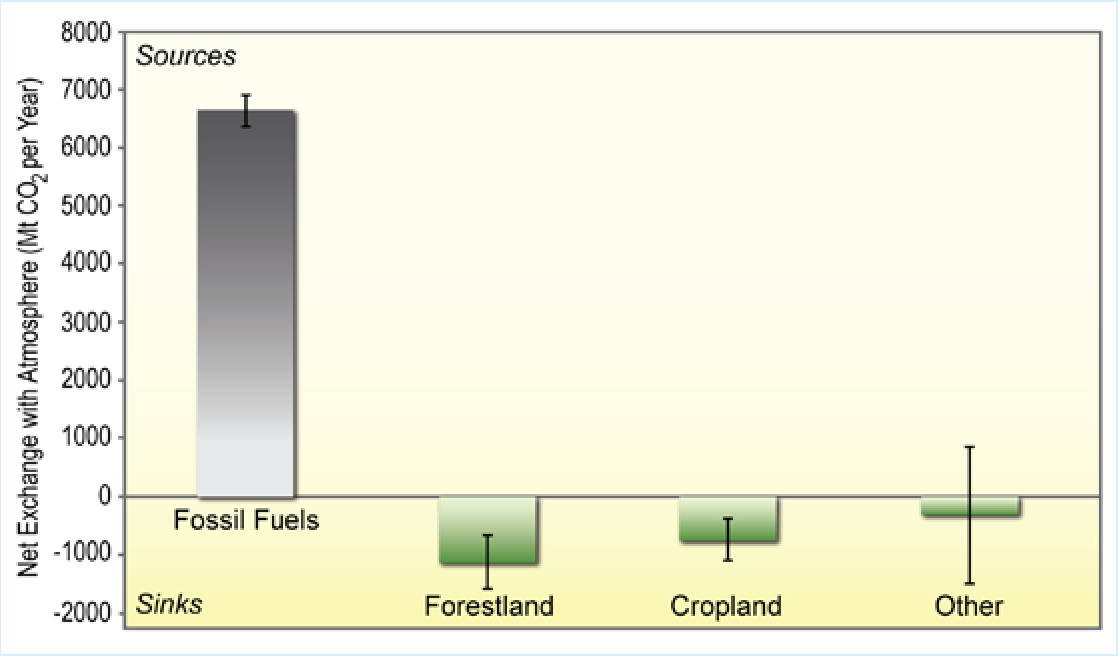

Figure 15.1. The release of carbon dioxide from fossil fuel burning in North America (shown here for 2010) vastly exceeds the amount that is taken up and temporarily stored in forests, crops, and other ecosystems (shown here is the annual average for 2000-2006). (Figure source: King et al. 2012[7]).

Sources and Fates of Reactive Nitrogen

The nitrogen cycle has been dramatically altered by human activity, especially by the use of nitrogen fertilizers, which have increased agricultural production over the past half century.[1,2] Although fertilizer nitrogen inputs have begun to level off in the U.S. since 1980,[12] human-caused reactive nitrogen inputs are now at least five times greater than those from natural sources.[13,14,15,16] At least some of the added nitrogen is converted to nitrous oxide (N_2O), which adds to the greenhouse effect in Earth's atmosphere.

An important characteristic of reactive nitrogen is its legacy. Once created, it can, in sequence, travel throughout the environment (for example, from land to rivers to coasts, sometimes via the atmosphere), contributing to environmental problems such as the formation of coastal low-oxygen "dead zones" in marine ecosystems in summer. These problems persist until the reactive nitrogen is either captured and stored in a long-term pool, like the mineral layers of soil or deep ocean sediments, or converted back to nitrogen gas.[17,18] The nitrogen cycle affects atmospheric concentrations of the three most important human-caused greenhouse gases: carbon dioxide, methane, and nitrous oxide. Increased available nitrogen stimulates the uptake of carbon dioxide by plants, the release of methane from wetland soils, and the production of nitrous oxide by soil microbes.

Human Activities that Form Reactive Nitrogen and Resulting Consequences in Environmental Reservoirs

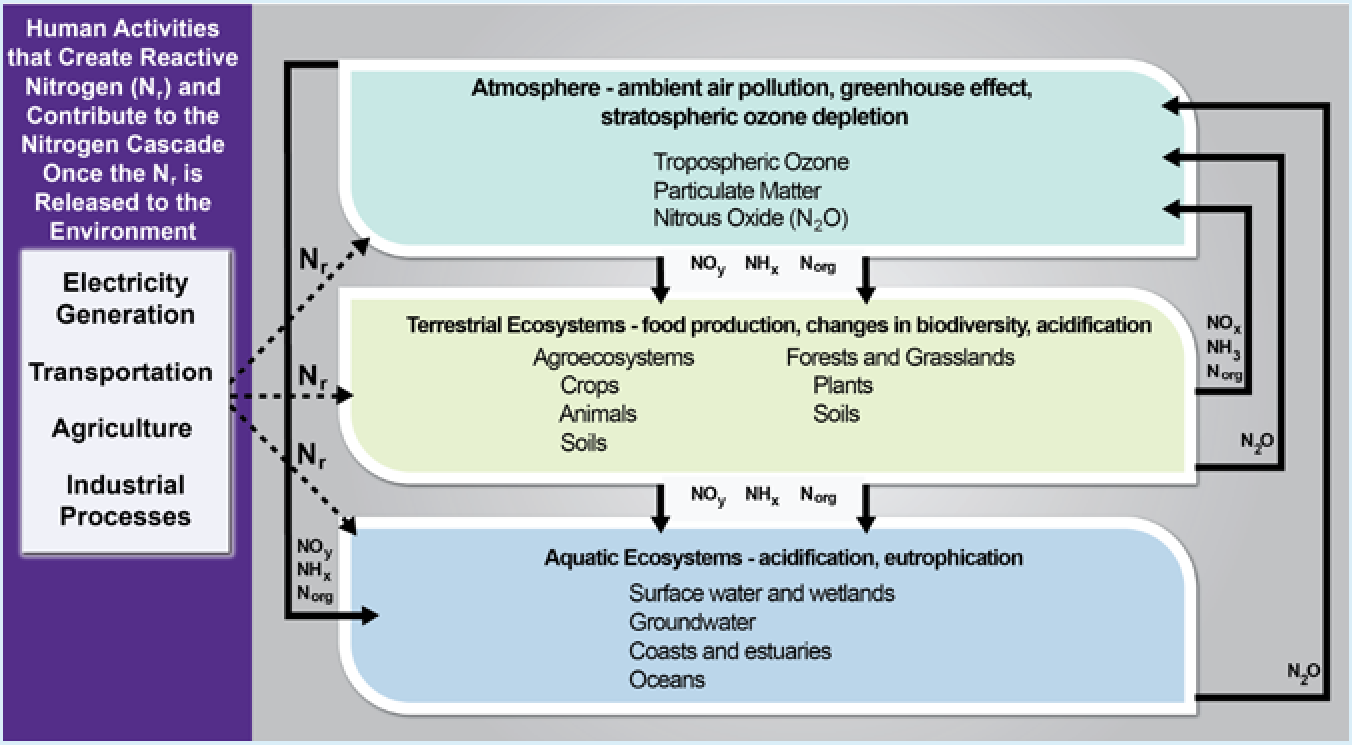

Figure 15.2. Once created, a molecule of reactive nitrogen has a cascading impact on people and ecosystems as it contributes to a number of environmental issues. Molecular terms represent oxidized forms of nitrogen primarily from fossil fuel combustion (such as nitrogen oxides, NO_x), reduced forms of nitrogen primarily from agriculture (such as ammonia, NH_3), and organic forms of nitrogen (N_{org}) from various processes. NO_y is all nitrogen-containing atmospheric gases that have both nitrogen and oxygen, other than nitrous oxide (N_2O). NH_x is the sum of ammonia (NH_3) and ammonium (NH_4). (Figure source: adapted from EPA 2011;[13] Galloway et al. 2003;[17] with input from USDA. USDA contributors were Adam Chambers and Margaret Walsh).

Phosphorus and other elements

The phosphorus cycle has been greatly transformed in the United States,[19] primarily from the use of phosphorus fertilizers in agriculture. Phosphorus has no direct effects on climate, but does have indirect effects, such as increasing carbon sinks by fertilizing plants. Emissions of sulfur, as sulfur dioxide, can reduce the growth of plants and stimulate the leaching of soil nutrients needed by plants.[20]

Key Message 2: Sinks and Cycles

In total, land in the United States absorbs and stores an amount of carbon equivalent to about 17% of annual U.S. fossil fuel emissions. U.S. forests and associated wood products account for most of this land sink. The effect of this carbon storage is to partially offset warming from emissions of CO_2 and other greenhouse gases.

Considering the entire atmospheric CO_2 budget, the temporary net storage on land is small compared to the sources: more CO_2 is emitted than can be taken up (see "Estimating the U.S. Carbon Sink").[7,21,22,23] Other elements and compounds affect that balance by direct and indirect means (for example, nitrogen stimulates carbon uptake [direct] and nitrogen decreases the soil methane sink [indirect]). The net effect on Earth's energy balance from changes in major biogeochemical cycles (carbon, nitrogen, sulfur, and phosphorus) depends upon processes that directly affect how the planet absorbs or reflects sunlight, as well as those that indirectly affect concentrations of greenhouse gases in the atmosphere.

Carbon

In addition to the CO_2 effects described above, other carbon-containing compounds affect climate change, such as methane and volatile organic compounds (VOCs). As the most abundant non-CO_2 greenhouse gas, methane is 20 to 30 times more potent than CO_2 over a century timescale. It accounted for 9% of all human-caused greenhouse gas emissions in the United States in 2011,[8] and its atmospheric concentration today is more than twice that of pre-industrial times.[24,25] Methane has an atmospheric lifetime of about 10 years before it is oxidized to CO_2, but it has about 25 times the global warming potential of CO_2. An increase in methane concentration in the industrial era has contributed to warming in many ways.[26]

Methane also has direct and indirect effects on climate because of its influences on atmospheric chemistry. Increases in atmospheric methane and VOCs are expected to deplete concentrations of hydroxyl radicals, causing methane to persist in the atmosphere and exert its warming effect for longer periods.[25,27] The hydroxyl radical is the most important "cleaning agent" of the troposphere (the active weather layer extending up to about 5 to 10 miles above the ground), where it is formed by a complex series of reactions involving ozone and ultraviolet light.[3]

Nitrogen and Phosphorus

The climate effects of an altered nitrogen cycle are substantial and complex.[4,28,29,30,31] Carbon dioxide, methane, and nitrous oxide contribute most of the human-caused increase in climate forcing, and the nitrogen cycle affects atmospheric concentrations of all three gases. Nitrogen cycling processes regulate ozone (O_3) concentrations in the troposphere and stratosphere, and produce atmospheric aerosols, all of which have additional direct effects on climate. Excess reactive nitrogen also has multiple indirect effects that simultaneously amplify and mitigate changes in climate. Changes in ozone and organic aerosols are short-lived, whereas changes in carbon dioxide and nitrous oxide have persistent impacts on the atmosphere.

Nitrogen Emissions

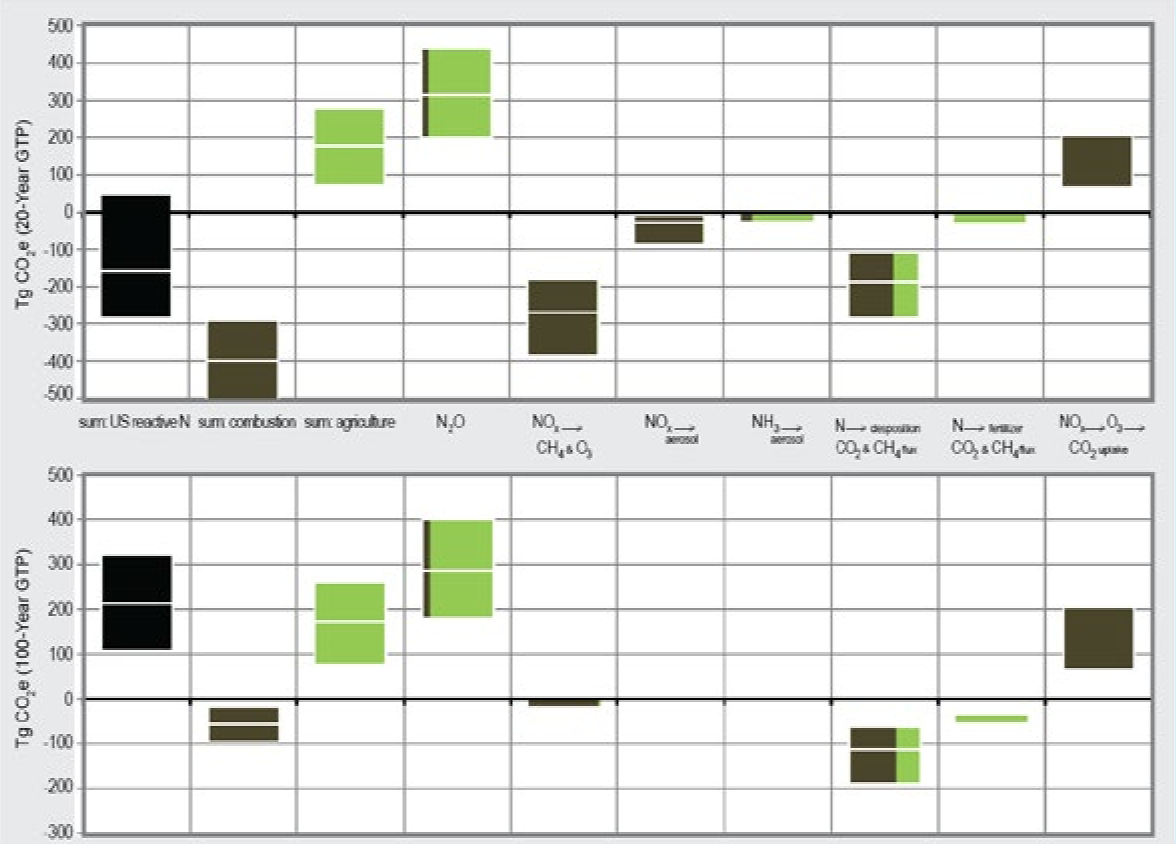

Figure 15.3. Figure shows how climate change will affect U.S. reactive nitrogen emissions, in Teragrams (Tg) CO_2 equivalent, on a 20-year (top) and 100-year (bottom) global temperature potential basis. Positive values on the vertical axis depict warming; negative values reflect cooling. The height of the bar denotes the range of uncertainty, and the white line denotes the best estimate. The relative contribution of combustion (dark brown) and agriculture (green) is denoted by the color shading. (Figure source: adapted from Pinder et al. 2012[28]).

The strongest direct effect of an altered nitrogen cycle is through emissions of nitrous oxide (N_2O), a long-lived and potent greenhouse gas that is increasing steadily in the atmosphere.[25,26] Globally, agriculture has accounted for most of the atmospheric rise in N_2O.[32,33] Roughly 60% of agricultural N_2O derives from elevated soil emissions resulting from the use of nitrogen fertilizer. Animal waste treatment accounts for about 30%, and the remaining 10% comes from crop-residue burning.[34] The U.S. reflects this global trend: around 75% to 80% of U.S. human-caused N_2O emissions are due to agricultural activities, with the majority being emissions from fertilized soil. The remaining 20% is derived from a variety of industrial and energy sectors.[35,36] While N_2O currently accounts for about 6% of human-caused warming,[26] its long lifetime in the atmosphere and rising concentrations will increase N_2O-based climate forcing over a 100-year time scale.[33,37,38]


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Excess reactive nitrogen indirectly exacerbates changes in climate by several mechanisms. Emissions of nitrogen oxides (NO_x) increase the production of tropospheric ozone, which is a greenhouse gas.[39] Elevated tropospheric ozone may reduce CO_2 uptake by plants and thereby reduce the terrestrial CO_2 sink.[40] Nitrogen deposition to ecosystems can also stimulate the release of nitrous oxide and methane and decrease methane uptake by soil microbes.[41]

However, excess reactive nitrogen also mitigates changes in greenhouse gas concentrations and climate through several intersecting pathways. Over short time scales, NO_x and ammonia emissions lead to the formation of atmospheric aerosols, which cool the climate by scattering or absorbing incoming radiation and by affecting cloud cover.[26,42] In addition, the presence of NO_x in the lower atmosphere increases the formation of sulfate and organic aerosols.[43] At longer time scales, NO_x can increase rates of methane oxidation, thereby reducing the lifetime of this important greenhouse gas.

One of the dominant effects of reactive nitrogen on climate stems from how it interacts with ecosystem carbon capture and storage, and thus, the carbon sink. As mentioned previously, addition of reactive nitrogen to natural ecosystems can increase carbon storage as long as other factors are not limiting plant growth, such as water and nutrient availability.[44] Nitrogen deposition from human sources is estimated to contribute to a global net carbon sink in land ecosystems of 917 to 1,830 million metric tons (1,010 to 2,020 million tons) of CO_2 per year. These are model-based estimates, as comprehensive, observationally-based estimates at large spatial scales are hindered by the limited number of field experiments. This net land sink represents two components: 1) an increase in vegetation growth as nitrogen limitation is alleviated by human-caused nitrogen deposition, and 2) a contribution from the influence of increased reactive nitrogen availability on decomposition. While the former generally increases with increased reactive nitrogen, the net effect on decomposition in soils is not clear. The net effect on total ecosystem carbon storage was an average of 37 metric tons (41 tons) of carbon stored per metric ton of nitrogen added in forests in the U.S. and Europe.[45]

When all direct and indirect links between reactive nitrogen and climate in the U.S. are added up, a recent estimate suggests a modest reduction in the rate of warming in the near term (next several decades), but a progressive switch to greater net warming over a 100-year timescale.[28,29] That switch is due to a reduction in nitrogen oxide (NO_x) emissions, which provide modest cooling effects, a reduction in the nitrogen-stimulated CO_2 storage in forests, and a rising importance of agricultural nitrous oxide emissions. Current policies tend to reinforce this switch. For example, policies that reduce nitrogen oxide and sulfur oxide emissions have large public health benefits, but also reduce the indirect climate mitigation co-benefits by reducing carbon storage and aerosol formation.

Changes in the phosphorus cycle have no direct effects on climate, but phosphorus availability constrains plant and microbial activity in a wide variety of land- and water-based ecosystems.[46,47] Changes in phosphorus availability due to human activity can therefore have indirect impacts on climate and the emissions of greenhouse gases in a variety of ways. For example, in land-based ecosystems, phosphorus availability can limit both CO_2 storage and decomposition[46,48] as well as the rate of nitrogen accumulation.[49] In turn, higher nitrogen inputs can alter phosphorus cycling via changes in the production and activity of enzymes that release phosphorus from decaying organic matter,[50] creating another mechanism by which rising nitrogen inputs can stimulate carbon uptake.

Other Effects: Sulfate Aerosols

In addition to the aerosol effects from nitrogen mentioned above, there are both direct and indirect effects on climate from other aerosol sources. Components of the sulfur cycle exert a cooling effect through the formation of sulfate aerosols created from the oxidation of sulfur dioxide (SO_2) emissions.[26] In the United States, the dominant source of sulfur dioxide is coal combustion. Sulfur dioxide emissions rose until 1980, but have since decreased by more than 50% following a series of air-quality regulations and incentives focused on improving human health and the environment, as well as reductions in the delivered price of low-sulfur coal.[51] That decrease in emissions has had a marked effect on U.S. climate forcing: between 1970 and 1990, sulfate aerosols caused cooling, primarily over the eastern U.S., but since 1990, further reductions in sulfur dioxide emissions have reduced the cooling effect of sulfate aerosols by half or more.[42] Continued declines in sulfate aerosol cooling are projected for the future,[42] particularly if coal continues to be replaced by natural gas (which contains far fewer sulfur impurities) for electricity generation. Here, as with nitrogen oxide emissions, the environmental and socioeconomic tradeoffs are important to recognize: lower sulfur dioxide and nitrogen oxide emissions remove some climate cooling agents, but improve ecosystem health and save lives.[16,31,52]

Three low-concentration industrial gases are particularly potent for trapping heat: nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), and trifluoromethyl sulfur pentafluoride (SF_5CF_3). None currently makes a major contribution to climate forcing, but since their emissions are increasing and their effects last for millennia, continued monitoring is important.

Key Message 3: Impacts and Options

Altered biogeochemical cycles together with climate change increase the vulnerability of biodiversity, food security, human health, and water quality to changing climate. However, natural and managed shifts in major biogeochemical cycles can help limit rates of climate change.

Climate change alters key aspects of biogeochemical cycling, creating the potential for feedbacks that alter both warming and cooling processes into the future. For example, as soils warm, the rate of decomposition will increase, adding more CO_2 to the atmosphere. In addition, both climate and biogeochemistry interact strongly with environmental and ecological concerns, such as biodiversity loss, freshwater and marine eutrophication (unintended fertilization of aquatic ecosystems that leads to water quality problems), air pollution, human health, food security, and water resources. Many of the latter connections are addressed in other sections of this assessment, but we summarize some of them here because consideration of mitigation and adaptation options for changes in climate and biogeochemistry often requires this broader context.

Climate-Biogeochemistry Feedbacks

Both rising temperatures and changes in water availability can alter climate-relevant biogeochemical processes. For example, as summarized above, nitrogen deposition drives temperate forest carbon storage, both by increasing plant growth and by slowing organic-matter decomposition.[53] Higher temperatures will counteract soil carbon storage by increasing decomposition rates and subsequent emission of CO_2 via microbial respiration. However, that same increase in decomposition accelerates the release of reactive nitrogen (and phosphorus) from organic matter, which in turn can fuel additional plant growth.[44] Temperature also has direct effects on net primary productivity (the total amount of CO_2 stored by a plant through photosynthesis minus the amount released through respiration). The combined effects on ecosystem carbon storage will depend on the extent to which nutrients constrain both net primary productivity and decomposition, on the extent of warming, and on whether any simultaneous changes in water availability occur.[54]

Similarly, natural methane sources are sensitive to variations in climate; ice core records show a strong correlation between methane concentrations and warmer, wetter conditions.[55] Thawing permafrost in polar regions is of particular concern because it stores large amounts of methane that could potentially be released to the atmosphere.

Biogeochemistry, Climate, and Interactions with Other Factors

Societal options for addressing links between climate and biogeochemical cycles must often be informed by connections to a broader context of global environmental changes. For example, both climate change and nitrogen deposition can reduce biodiversity in water- and land-based ecosystems. The greatest combined risks are expected to occur where critical loads are exceeded.[56,57] A critical load is defined as the input rate of a pollutant below which no detrimental ecological effects occur over the long-term according to present knowledge.[57] Although biodiversity is often shown to decline when nitrogen deposition is high due to fossil fuel combustion and agricultural emissions,[57,58] the compounding effects of multiple stressors are difficult to predict. Warming and changes in water availability have been shown to interact with nitrogen in additive or synergistic ways to exacerbate biodiversity loss.[59] Unfortunately, very few multi-factorial studies have been done to address this gap.

Human induced acceleration of the nitrogen and phosphorus cycles already causes widespread freshwater and marine eutrophication,[60,61] a problem that is expected to worsen under a warming climate.[61,62] Without efforts to reduce future climate change and to slow the acceleration of biogeochemical cycles, existing climate changes will combine with increasing inputs of nitrogen and phosphorus into freshwater and estuarine ecosystems. This combination of changes is projected to have substantial negative effects on water quality, human health, inland and coastal fisheries, and greenhouse gas emissions.[18,61]

Similar concerns – and opportunities for the simultaneous reduction of multiple environmental problems (known as "co-benefits") – exist in the realms of air pollution, human health, and food security. For example, methane, volatile organic compounds, and nitrogen oxide emissions all contribute to the formation of tropospheric ozone, which is a greenhouse gas and has negative consequences for human health and crop and forest productivity.[37,63,64] Rates of ozone formation are accelerated by higher temperatures, creating a reinforcing cycle between rising temperatures and continued human alteration of the nitrogen and carbon cycles.[65] Rising temperatures also work against some of the benefits of air pollution control.[64] Some changes will trade gains in one arena for declines in others. For example, lowered NO_x, NH_x, and SO_x emissions remove cooling agents from the atmosphere, but improve air quality.[16,31] Recent analyses suggest that targeting reductions in compounds like methane and black carbon aerosols that have both climate and air-pollution consequences can achieve significant improvements in not only the rate of climate change, but also in human health.[31] Finally, reductions in excess nitrogen and phosphorus from agricultural and industrial activities can potentially reduce the rate and impacts of climate change, while simultaneously addressing concerns in biodiversity, water quality, food security, and human health.[66]

Many Factors Combine to Affect Biogeochemical Cycles

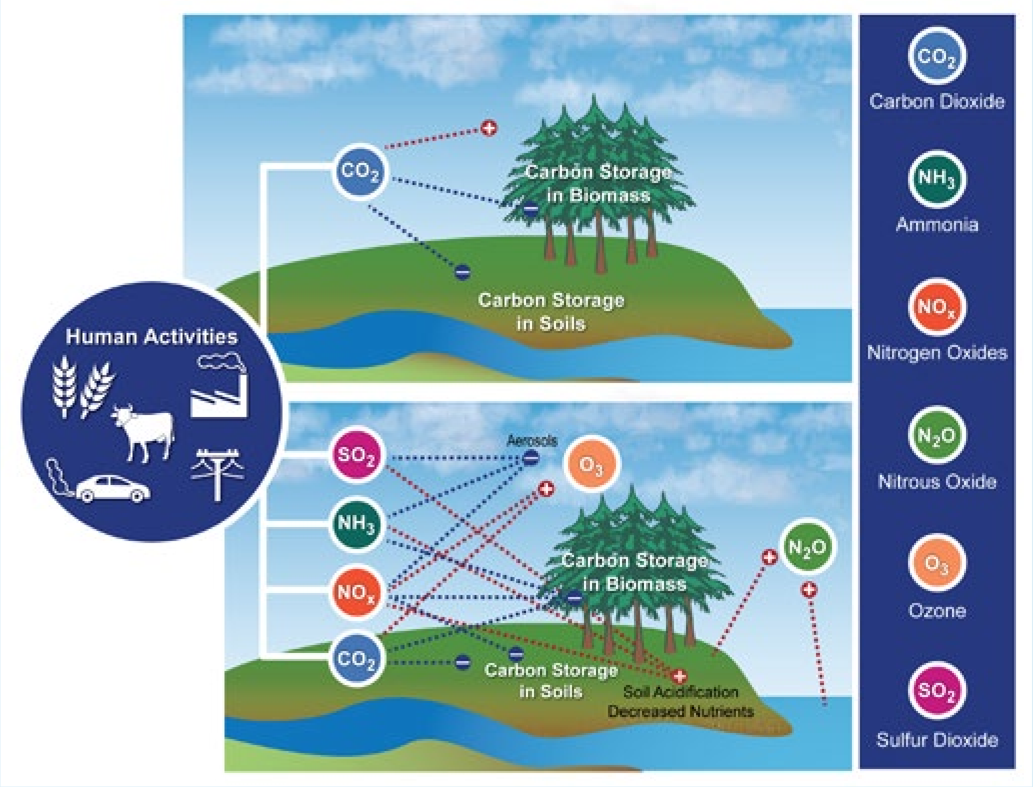

Figure 15.4. Top panel shows the impact of the alteration of the carbon cycle alone on radiative forcing. The bottom panel shows the impacts of the alteration of carbon, nitrogen, and sulfur cycles on radiative forcing. SO_2 and NH_3 increase aerosols and decrease radiative forcing. NH_3 is likely to increase plant biomass, and consequently decrease forcing. NO_x is likely to increase the formation of tropospheric ozone (O_3) and increase radiative forcing. Ozone has a negative effect on plant growth/biomass, which might increase radiative forcing. CO_2 and NH_3 act synergistically to increase plant growth, and therefore decrease radiative forcing. SO_2 is likely to reduce plant growth, perhaps through the leaching of soil nutrients, and consequently increase radiative forcing. NO_x is likely to reduce plant growth directly and through the leaching of soil nutrients, therefore increasing radiative forcing. However, it could act as a fertilizer that would have the opposite effect.

ESTIMATING THE U.S. CARBON SINK

Any natural or engineered process that temporarily or permanently removes and stores carbon dioxide (CO_2) from the atmosphere is considered a carbon "sink." Temporary (10 to 100 years) CO_2 sinks at the global scale include absorption by plants as they photosynthesize, as well as CO_2 dissolution into the ocean. Forest biomass and soils in North America offer large temporary carbon sinks in the global carbon budget; however, the spatial distribution, longevity, and mechanisms controlling these sinks are less certain.[67] Understanding these processes is critical for predicting how ecosystem carbon sinks will change in the future, and potentially for managing the carbon sink as a mitigation strategy for climate change.

Table 15.1. Carbon (C) sinks and uncertainty estimated by Pacala et al. for the first State of the Carbon Cycle Report.[23] Forests take up the highest percentage of carbon of all land-based carbon sinks. Due to a number of factors, there are high degrees of uncertainty in carbon sink estimates.

Land Area	C sink (Tg C/y) (95% CI)	Method
Forest	-256 (+/- 50%)	inventory, modeled
Wood products	-57 (+/- 50%)	inventory
Woody encroachment	-120 (+/- >100%)	inventory
Agricultural soils	-8 (+/- 50%)	modeled
Wetlands	-23 (+/- >100%)	inventory
Rivers and reservoirs	-25 (+/- 100%)	inventory
Net Land Sink	**-489 (+/- 50%)**	**inventory**

Both inventory (measurement) and modeling techniques have been used to estimate land-based carbon sinks at a range of scales in both time and space. For inventory methods, carbon stocks are measured at a location at two points in time, and the amount of carbon stored or lost can be estimated over the intervening time period. This method is widely used to estimate the amount of carbon stored in forests in the United States over timescales of years to decades. Terrestrial biosphere models estimate carbon sinks by modeling a suite of processes that control carbon cycling dynamics, such as photosynthesis (CO_2 uptake by plants) and respiration (CO_2 release by plants, animals, and microorganisms in soil and water). Field-based data and/or remotely sensed data are used as inputs and also to validate these models. Estimates of the land-based carbon sink can vary depending on the data inputs and how different processes are modeled.[22] Atmospheric inverse models use information about atmospheric CO_2 concentrations and atmospheric transport (like air currents) to estimate the terrestrial carbon sink.[68] This approach can provide detailed information about carbon sinks over time. However, because atmospheric CO_2 is well-mixed and monitoring sites are widely dispersed, these models estimate fluxes over large areas and it is difficult to identify processes responsible for the sink from these data.[22] Recent estimates using atmospheric inverse models show that global land and ocean carbon sinks are stable or even increasing globally.[69]

U.S. Carbon Sinks Absorb a Fraction of CO_2 Emissions

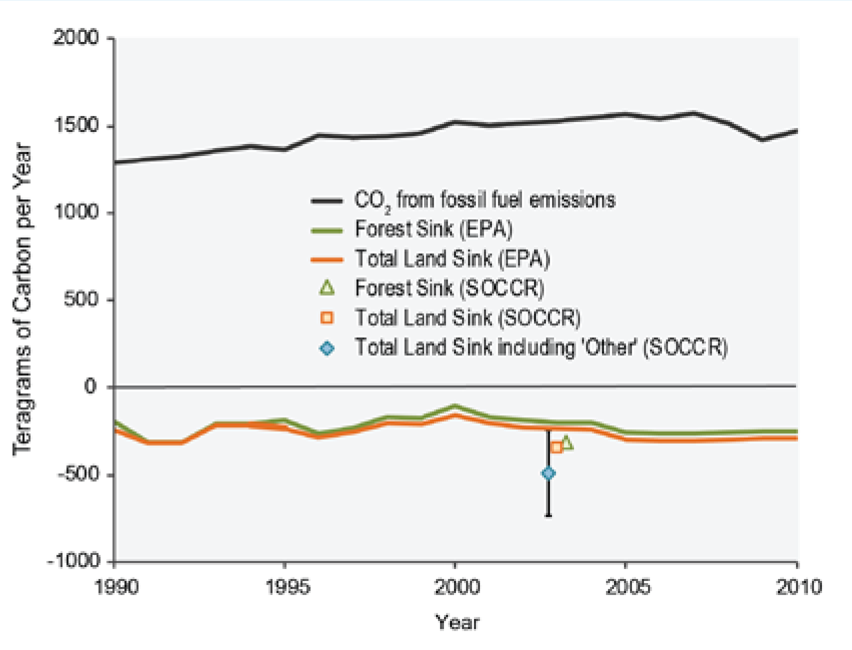

Figure 15.5. Figure shows growth in fossil fuel CO_2 emissions (black line) and forest and total land carbon sinks in the U.S. for 1990–2010 (green and orange lines; from EPA 2012[21]) and for 2003 (symbols; from the first State of the Carbon Cycle Report[67]). Carbon emissions are significantly higher than the total land sink's capacity to absorb and store them. (Data from EPA 2012 and CCSP 2007[21,67]).

Continued

ESTIMATING THE U.S. CARBON SINK (CONTINUED)

U.S. Carbon Sources and Sinks from 1991 to 2000 and 2001 to 2010

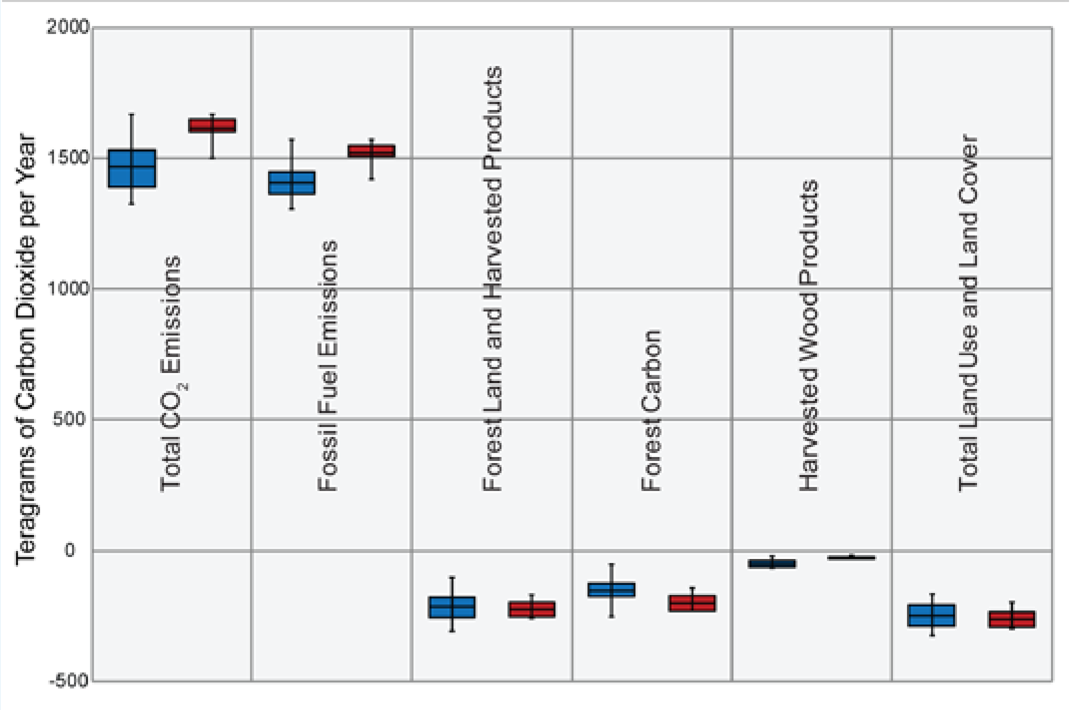

Figure 15.6. Changes in CO_2 emissions and land-based sinks in two recent decades, showing among-year variation (vertical lines: minimum and maximum estimates among years; boxes: 25th and 75th quartiles; horizontal line: median). Total CO_2 emissions, as well as total CO_2 emissions from fossil fuels, have risen; land-based carbon sinks have increased slightly, but at a much slower pace. (Data from EPA 2012 and CCSP 2007[21,67]).

The U.S. Environmental Protection Agency (EPA) conducts an annual inventory of U.S. greenhouse gas emissions and sinks as part of the nation's commitments under the Framework Convention on Climate Change. Estimates are based on inventory studies and models validated with field-based data (such as the CENTURY model) in accordance with the Intergovernmental Panel on Climate Change (IPCC) best practices.[70] An additional comprehensive assessment, The First State of the Carbon Cycle Report (SOCCR), provides estimates for carbon sources and sinks in the U.S. and North America around 2003.[67] This assessment also utilized inventory and field-based terrestrial biosphere models, and incorporated additional land sinks not explicitly included in EPA assessments.

Data from these assessments suggest that the U.S. carbon sink has been variable over the last two decades, but still absorbs and stores a small fraction of CO_2 emissions. The forest sink comprises the largest fraction of the total land sink in the United States, annually absorbing 7% to 24% (with a best estimate of 16%) of fossil fuel CO_2 emissions during the last two decades. Because the U.S. Forest Service has conducted detailed forest carbon inventory studies, the uncertainty surrounding the estimate for the forest sink is lower than for most other components (see Pacala et al. 2007, Table 2[23]). The role of lakes, reservoirs, and rivers in the carbon budget, in particular, has been difficult to quantify and is rarely included in national budgets.[71] The IPCC guidelines for estimating greenhouse gas sources or sinks from lakes, reservoirs, or rivers are included in the "wetlands" category, but only for lands converted to wetlands. These ecosystems are not included in the EPA's estimates of the total land sink. Rivers and reservoirs were estimated to be a sink in the State of the Carbon Cycle analysis,[23] but recent studies suggest that inland waters may actually be an important source of CO_2 to the atmosphere.[72] It is important to note that these two methods use different datasets, different models, and different methodologies to estimate land-based carbon sinks in the United States. In particular, we note that the EPA Inventory, consistent with IPCC Guidelines for national inventories, includes only carbon sinks designated as human-caused, while the SOCCR analysis does not make this distinction.

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